# NPDES Stormwater Cost Survey

Water Boards

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*Prepared For:*

*California State Water Resources Control Board*

*Prepared by:*

*Office of Water Programs*
*California State University, Sacramento*

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UNIVERSITY OF SOUTHERN CALIFORNIA

*Includes Appendix H:*

*Alternative Approaches to Stormwater Control*

*Prepared by:*

*Center for Sustainable Cities*
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*Contract: 02-189-250-0*

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# NPDES Stormwater Cost Survey
## Final Report


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# EXECUTIVE SUMMARY

This report is funded by the California State Water Resources Control Board under contract 02-189-250-0, "Survey of Costs to Develop, Implement, Maintain and Monitor Municipal Separate Storm Sewer System (MS4) Storm Water Management Programs and Description of Alternatives for Control of Stormwater Quality in Los Angeles County."

## BACKGROUND

The current costs to implement best management practices (BMPs) have been the basis for lawsuits and petitions challenging the California stormwater regulatory program. Additionally, some permittees contend that current MS4 permits necessitate the use of advanced water treatment to meet water quality standards, which would drastically escalate costs above current levels. This contention is presented in the report titled "An Economic Impact Evaluation of Proposed Storm Water Treatment for Los Angeles County" (Gordon, 2002). This project addresses these issues through two tasks.

### *Task A – Documenting Stormwater Program Costs*

Five California municipalities and one metropolitan area with stormwater programs that are demonstrating meaningful progress toward maximum extent practicable (MEP) compliance as identified by Regional Water Quality Control Board (RWQCB) staff were surveyed for the most recent stormwater compliance costs. Demonstrating meaningful progress is defined in this report as implementing activities specifically presented in the Storm Water Management Plans (SWMPs). Because permits use an iterative approach that increases requirements until water quality objectives are met, current levels of implementation may not be the ultimate MEP standard. This report does not address the benefits of permit compliance activities. Some scenarios addressing ultimate compliance cost are addressed in Task B. Task A was accomplished by the Office of Water Programs (OWP) at California State University, Sacramento (CSUS).

### *Task B – Alternative Approaches to Stormwater Quality Control*

Task B is an assessment of regulatory policy to determine the intent of stormwater regulation regarding advanced treatment. Alternatives for stormwater quality control that are believed to comply with the intent of the regulations are described. Costs were estimated for the Los Angeles Regional Water Quality Control Board (LARWQCB) area. Task B was accomplished by the University of Southern California (USC) and the University of California at Los Angeles (UCLA).

## RESULTS

### *Cost Survey (Task A)*

Annual cost per household for the six stormwater programs surveyed ranged from $18 to $46, as seen in Table 1.

# EXECUTIVE SUMMARY

**Table 1. Stormwater Costs per Household for the California Cost Survey (Task A)**

| Municipalities | Municipality Description | Cost/Household ($) |
|---|---|---|
| City of Encinitas | Coastal tourism, small city | 46 |
| City of Fremont | Bay Area, moderately integrated countywide program | 45 |
| City of Santa Clarita | Tourism and industrial | 39 |
| City of Corona | Industrial | 32 |
| City of Sacramento | Pumped stormwater, large city | 29 |
| Fresno-Clovis Metropolitan Area | 65-90% infiltration, fully integrated multi-city program | 18 |

The Fresno-Clovis Metropolitan Area (FCMA) had substantially lower cost per household. The following factors are thought to contribute to the FCMA stormwater costs being lower than the other survey results:

- flood control and stormwater quality basins are combined,
- land was set aside for water projects,
- climate helps infiltration due to infrequent storms and low annual rainfall,
- lower land cost compared to other cities,
- FMFCD owned land needed for basins prior to storm water permits requirements,
- topography lends to drainage of urban areas to post-construction BMPs, and
- highly permeable soils allow extensive use of infiltration.

These factors are unique or more prevalent for FCMA than for the other cities surveyed. Excluding the FCMA as an ideal situation, the range of cost is $29 to $46 per household.

The results of the survey are compared to values from the USEPA report "Economic Analysis of the Final Phase II Stormwater Rule." This report contains a summary of costs from two separate efforts to estimate Phase II cost per household. The first is the results of a survey stormwater costs for 56 Phase II municipalities performed by the National Association of Flood and Stormwater Management Agencies (NAFSMA). The NAFSMA survey represents the six minimum measures of the Phase II regulations because two measures seemed to have been combined: 1) Public Education and Outreach and 2) Public Involvement and Participation.

The second effort presented in the USEPA report is the results of a review by USEPA of annual stormwater reports from 26 Phase I municipalities. These municipalities were chosen were smaller Phase I cities, were nearly in the first permit term, and had reported cost in their annual reports. The California survey results for the cost categories corresponding to the six minimum measures were extracted to compare to the NAFSMA survey and the EPA review. The results of this comparison are in Table 2.

**Table 2. Stormwater Costs per Household for Six[1] Minimum Measures from the California Survey, the NAFSMA[2] Phase II Survey, and the USEPA review of Phase I Annual Reports (USEPA, 1999)**

| Study | Median (50%) ($) | Mean ($) | Max ($) |
|---|---|---|---|
| Adjusted California Survey[3] | 24 | 26 | 35 |
| NAFSMA Phase II Survey[4] | 4.63 | 10 | 61 |
| EPA Phase I Survey[5] | 3.16 | 10 | 67 |

1. Public Education and Outreach and Public Involvement and Participation were assumed combined for the NAFSMA survey.
2. NAFSMA: National Association of Flood and Stormwater Management Agencies
3. Based only on costs from cost categories that correspond to the six minimum measures
4. NAFSMA survey based on 56 Phase II respondents to a survey on stormwater costs for five minimum measures. Values adjusted to 2003 dollars.
5. EPA results based on a review of 26 annual reports for smaller Phase I cities that were nearly in their first NPDES term so that costs would be more representative of Phase II programs. Values adjusted to 2003 dollars.

In some cases, programs in the California survey appeared to go beyond the minimum requirements of the permit. The cost of this additional effort was not included when it could be identified or estimated, such as street sweeping in Sacramento that was above the permit required frequency. Including the total cost of the street sweeping program the cost per household for Sacramento would increase $1.69. In some cases the additional effort could not be estimated. This was particularly true when stormwater activities were combined with activities that occurred more frequently than the permit requirement for the stormwater activities, such as when stormwater construction inspections for Santa Clarita were performed at every construction permit inspection and these permit inspections occurred more frequently than the permit requirement.

*Description of Alternatives for Control of Stormwater Quality (Task B)*

The alternatives for control of stormwater quality focus on source control and runoff reduction. The principle strategy for runoff reduction is by infiltration and evapotranspiration, using common BMPs. Based on this approach, costs for two scenarios are estimated for the area under LARWQCB jurisdiction. One scenario assumes source control BMPs are sufficient to comply with regulations. The other scenario assumes treatment using wetlands and infiltration basins. Two costs were estimated for the treatment scenario based on two different sources of unit costs. These scenarios do not include advanced treatment costs. Equivalent annual costs per household were calculated to compare to cost estimates from other studies. Table 3 compares the cost estimates of the two scenarios to the estimated current stormwater cost for the Los Angeles area.

Current level of effort in the Los Angeles area has only made limited progress in implementing the scenarios described in Task B (Devinny, 2004). If there are cases where discharge from these BMPs still requires advanced treatment, the cost of stormwater treatment would be much less than if advanced treatment was solely used because runoff reductions would reduce the size of treatment plant requirements.

**Table 3. Equivalent Cost Per Household For Task B Alternatives**

| Cost Scenario for the Los Angeles Area | Equivalent Annual Cost, $/household |
|---|---|
| Current Effort | 18 |
| Alternative to Advanced Treatment: Pollution Prevention Scenario (Present worth 2.8 billion)[1] | 27 |
| Alternative to Advanced Treatment: Wetlands and Infiltration Basins Scenario, calculated using cost per area (Present worth 5.7 billion)[1] | 55 |
| Alternatives to Advanced Treatment: Wetlands and Infiltration Basins Scenario, calculated using cost per capture volume (present worth 7.4 billion)[1] | 71 |

1. Little progress has been made in implementing these scenarios (Devinny, pers. comm., 9/14/04). These costs may be added to the current effort if existing programs continue to be required. Costs based on Devinny et. al. (Appendix H), see Table G-6 for equivalent annual cost calculation.

Table 4 compares several cost estimates in terms of equivalent annual cost per household.

**Table 4. Equivalent Annual Cost per Household Comparisons between California Cost Survey Results and Los Angeles Area Future Cost Estimates[1]**

| Range of Current Cost from the California Survey | | Range of Cost Estimates for Alternatives for Control of Stormwater Quality[2] | | Maximum TMDL Estimates[3] | | Statewide Clean Water Willingness To Pay[4] |
|---|---|---|---|---|---|---|
| | | | | Ballona Creek Metals | L.A. River Trash | |
| 18 | 46 | 27 | 71 | 75 | 141 | 180 |

1. Calculations are presented in Appendix G and are based on the following sources for each column respectively: survey results in Section 9, Devinny et al (Appendix H), RWQCB, Los Angeles (2004), LARQCB (2001), and Larsen and Lew (2003).
2. Calculated from Task B in Appendix H. Low range is the cost for attaining full compliance using only source control. High range is the cost for attaining full compliance using only treatment BMPs (low tech) estimated on capture volume. It is estimated that this is in addition to the current level of spending in the Los Angeles area.
3. TMDL costs apply to all sources, not just MS4 stormwater sources.
4. Responses were not received from 40% of the mailed surveys. The survey question was for restoring water quality for all waters throughout the state from all impairment, not just within a city or region and not just for impairment from stormwater pollution.

The costs developed by Gordon et al. (2002) were based on capture, collection and advanced treatment of various percentages of the annual runoff volume. An annual runoff capture volume of 70 percent (0.5-inch storm) was selected to compare to the Los Angeles Standard Urban Stormwater Mitigation Plan (SUSMP) capture standards of around 85 percent (0.75-inches). Unfortunately, the next highest capture volume analyzed by Gordon was the 1.25-inch storm. The resulting equivalent annual cost per household using the 0.5-inch storm and assuming a treatment scenario of 65 large regional treatment plants is $459/household. This cost only estimates cost that the cities in Los Angeles County would incur, so they may not directly comparable to the total watershed costs developed in the Total Maximum Daily Load (TMDL) plans because TMDL costs are not restricted to stormwater quality control.

Since some advanced treatment may be required, the future cost will lie between the alternative scenarios estimate and the advanced treatment estimate. Based on the assumption used by the Devinny study, future costs for the Los Angeles area appear to hinge on the ability to reduce stormwater runoff volumes and on the ability to control pollutants through source control.

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## 1.1 BACKGROUND

The 1987 amendments to the federal Clean Water Act (CWA) added Section 402(p), which defined stormwater discharges from industrial activities and municipal systems as point sources subject to the National Pollutant Discharge Elimination System (NPDES) Permit Program. The CWA directed the United States Environmental Protection Agency (USEPA) to publish regulations to define the discharges subject to NPDES permits and to establish a framework for regulating these discharges. The stormwater regulations promulgated by USEPA established a two-phase approach for municipal systems. The first phase began in 1990 and addressed discharges from (MS4s) that serve populations greater than 100,000 people. The second phase began in 1999 and addressed discharges from MS4s that serve populations less than 100,000 and are located in urbanized areas. The State Water Resources Control Board and the Regional Water Quality Control Boards (RWQCBs) can apply the Phase I or Phase II rules to areas with smaller populations as needed to protect water quality.

The CWA and federal stormwater regulations require MS4s subject to NPDES permits to reduce the pollutants in stormwater discharges to the maximum extent practicable (MEP). The regulations require the implementation of best management practices (BMPs) to meet the MEP discharge standard. BMPs include both source controls and treatment measures. MS4s are to implement an effective combination of these BMPs to reduce pollutants in stormwater discharges. In California, MS4 permits also require permittees to reduce the discharge of pollutants so that water quality standards are met. However, the permits do not specify strict compliance with numeric water quality standards. Rather, the MS4 permits require the compliance with standards through an iterative approach. Permittees implement BMPs according to storm water management plans. (If the current level of effort does not achieve water quality standards, additional BMPs are implemented until compliance has been achieved).

The current costs to implement BMPs have been the basis for lawsuits and petitions challenging the California stormwater regulatory program. Additionally, some permittees contend that current MS4 permits necessitate the use of advanced water treatment to meet water quality standards, which would drastically escalate costs above current levels (Gordon, 2001). Neither the USEPA nor the SWRCB has estimated costs for the development and implementation of MS4 stormwater programs to achieve MEP. The SWRCB and RWQCBs wish to respond to the contention that the intent of the California stormwater program is to require all stormwater discharges to be treated with advanced treatment devices. This project addresses these issues through two tasks.

**Task A – Documenting Stormwater Program Costs**

Documenting costs of a subset of California MS4 stormwater programs that were identified by RWQCB staff as demonstrating meaningful progress toward MEP compliance will aid in approximating costs of permit compliance statewide. Making meaningful progress is considered implementing activities specifically presented in the SWMPs. Stormwater program expenditures by those municipalities were compiled. The cost data was analyzed and normalized to identify potential cost factors that can be used to estimate costs for other municipalities to achieve permit compliance. Although compliance with construction and industrial permits is discussed in stormwater permits, the compliance costs for these permits are not included in this report. This report does not address the benefits of permit compliance activities[1].

Only municipal costs are documented; total societal costs are not. There are additional costs borne by developers (passed onto homeowners), businesses, industries and residents that are not addressed in Task A. The Task A was accomplished by personnel from the Office of Water Programs at CSUS.

**Task B – Alternative Approaches to Stormwater Quality Control**

Task B is an assessment of regulatory policy to determine the intent of stormwater regulation regarding advanced treatment. Alternatives for stormwater quality control that are believed to comply with the intent of the regulations are described and costs are estimated for the Los Angeles Regional Water Quality Control Board (LARWQCB) area. The intent of the regulation was determined by speaking with LARWQCB staff and reviewing past regulatory action. Task B was accomplished by faculty from the University of Southern California and the University of California Los Angeles. This task assumes the MS4 permitting process as it stands presently, using an iterative process of enhancing implementation of BMPs. This scenario may overlap with the Total Maximum Daily Load (TMDL) process, but it is not necessarily the same since the TMDL process address pollution sources other than stormwater.

## 1.2 REPORT ORGANIZATION

Task A is addressed in Sections 2 through 9. Section 2 presents the methodology for gathering, analyzing, and presenting cost information. Sections 3 through 8 present the NPDES-related stormwater costs and other relevant characteristics for the six municipal areas surveyed. The raw cost data and description of how program costs were developed are shown in Appendices A through F. In Section 9, normalized costs for each major stormwater program element are presented and compared between cities. Explanations for the observed differences are also offered. Appendix G contains the backup calculations for Section 9. Section 10 presents

[1] A subcommittee of the California Stormwater Quality Association (CASQA) is working on developing guidelines for program effectiveness evaluation, which has an ultimate goal of quantifying changes in receiving water quality (the benefit) due to stormwater activities.

recommendations for further cost reporting and analysis. References are in Section 11. Task B is included as Appendix H.

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The method for data collection, organization, and quality evaluation is presented in this section. Data sources are also described. Methodology and assumption for Task B are reviewed in the Executive Summary of the report found in Appendix H.

## 2.1 TECHNICAL ADVISORY GROUP

A technical advisory group (TAG) was formed to assist in the execution of this project. The TAG was comprised of one representative from USEPA, one from RWQCB, three from universities not associated with executing the study, one consultant, and one representative from the California Stormwater Quality Association (CASQA)[2]. TAG members reviewed and commented on each major phase of the study, including the initial city selection, initial scope of the study, initial results from the first city, and the interim draft report. A description of the TAG and their comments are included in Appendix J. The TAG did not review the work done for Task B (Appendix H).

## 2.2 CITY SELECTION

The following criteria were used in the selection process:

- nominated by RWQCB staff as having a good stormwater program,
- a variety of geographic and hydrologic areas within California,
- have a stormwater fund or equivalent that required the cities to track stormwater costs,
- a variety of populations, with at least one city below 100,000, and
- a variety of income per population or household.

Initial nominations and selection recommendations were presented in a memorandum to the SWRCB (Appendix I). Subsequent discussion with cities and RWQCB staff refined the list. One nominee, Corona, was considered after the memorandum was submitted. All the cities nominated for the inland area of Southern California were not able to participate, so the RWQCB then nominated Corona. Corona was not initially considered because of a lack of familiarity with the progress of their stormwater program. Subsequent review established Corona as a nominee.

The following municipalities were selected and agreed to participate in the cost survey:

- Corona
- Encinitas
- Fremont
- Fresno-Clovis Metropolitan Area
- Sacramento
- Santa Clarita

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[2] CASQA is a non-profit organization with mostly municipality membership. CASQA advises the California SWRCB on stormwater issues.

The locations of the participating municipalities are shown in Figure 2-1.

## 2.3 COST SURVEY CATEGORIES

The Cost Survey Categories were based on the USEPA six minimum measures for Phase II stormwater programs because cities often report cost in annual reports for several of these categories (http://cfpub.epa.gov/npdes/stormwater/menuofbmps/menu.cfm). The six categories initially considered in this study were:

- Public Education and Outreach,
- Public Involvement and Participation,
- Illicit Discharge Detection and Elimination (a.k.a. Illicit Connection and Illicit Discharge),
- Construction Site Stormwater Runoff Control,
- Post Construction Stormwater Management in New Development and Redevelopment, and
- Pollution Prevention and Good Housekeeping for Municipal Operations.

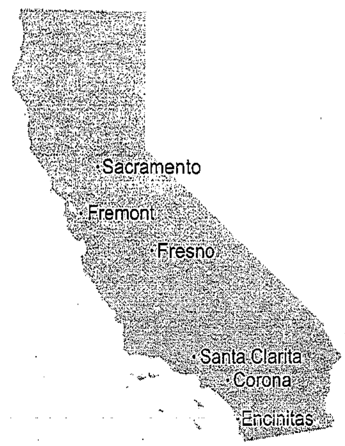



**Figure 2-1. Location of Municipal Areas Selected for the Cost Survey**

For several cities, Public Education and Outreach and the Public Involvement and Participation costs were not tracked separately. Consequently, differentiating costs between these two categories was often impractical. For these cities, these costs are reported in a "Public Education, Outreach, Involvement, and Participation" category.

Review of the stormwater permits of the selected cities and consultation with SWRCB staff resulted in these additional categories:

- Industrial and Commercial Management Programs,
- Overall Stormwater Program Management,
- Water Quality Monitoring, and
- Watershed Management.

The industrial and commercial management programs were combined because most of the selected cities did not differentiate between the costs associated with industrial sites and commercial sites.

The Watershed Management category includes costs associated with participation in total maximum daily load (TMDL) development processes and watershed management addressing

303(d)[3] pollutants. Most of the cities are not actively implementing TMDLs and costs reported in this category do not include TMDL implementation activities. Furthermore, existing TMDLs suggest stormwater compliance will be through enhancement to current permit compliance activities such as post-construction BMPs.

## 2.4 IDENTIFYING NEW, EXISTING, AND ENHANCED COSTS

All costs were identified as new, existing, or enhanced according to the extent that the activities existed before the first stormwater permit. New costs are for activities that are exclusively a result of compliance efforts with the stormwater permit. Existing costs are for activities that predated stormwater permits. Enhanced costs are for existing activities that were increased due to permit requirements. Enhanced costs are the total cost for impacted activities. It is not the increase in cost due to permit requirements. This number would have to be developed from 1990 baseline costs, and this is beyond the scope of this project.

## 2.5 DATA COLLECTION

Because costs for the 2003/2004 fiscal year were not available at the start of this survey, costs for the 2002/2003 fiscal year were collected.

Initially, a questionnaire was developed to facilitate the data collection effort. Questions were developed to capture cost data and descriptions of the stormwater program activities for each city. The questionnaire was organized by cost category and included questions for individual activities or BMPs within each cost category. The questionnaire was given to the city of Sacramento as a test case, but it proved difficult to use as the cost information and description of activities/BMPs available to city staff did not match well with those in the questionnaire. Consequently, the questionnaire was abandoned as the primary data collection tool, though it was shared with other cities as a guide to help staff understand what type of information was being sought.

The data collection methodology is depicted in Figure 2-2. City staff members were contacted by email and with follow-up telephone conversations in which the purpose and scope of the study were described. As mentioned above, a copy of the questionnaire was sent as guidance material. City staff then submitted cost and activity data in whatever format was available. The documents that usually contained the most useful information were the city's annual stormwater report, cost spreadsheets submitted by city staff, the NPDES stormwater permit, and SWMPs, or Stormwater Quality Improvement Plans (SQIPs), or Drainage Area Master Plans (DAMPs).

The next step was to fit the information provided into the cost survey categories. This wasn't always straightforward as there were significant differences among cities in the format and

[3] The term 303(d) pollutants are used here to describe the pollutants in specific waters for which TMDLs are being developed according to Section 303(d) of the CWA.

content of annual stormwater reports. For example, the annual stormwater report for one city was divided into two separate submittals, each covering one half of the year. The study team combined data from each section to represent the whole year. In another example, the annual stormwater reports of two cities did not contain costs. In these cases, cost and activity data was assembled from multiple alternate sources. After working through a variety of reporting formats, costs were allocated among the cost survey categories and entered into tables similar to Table 2-1. These tables were returned to the surveyed cities to give them an opportunity to comment on the allocation of costs. Follow up inquiries were also made when data was incomplete or missing. Data collection, cost allocation, and coordination with the surveyees' continued until all substantial questions were answered. Coordination with city staff members usually resulted in adjustments that more accurately accounted for those stormwater activities related to permit compliance.

**Table 2-1. Example of Cost Information Collected for Each Cost Survey Category**

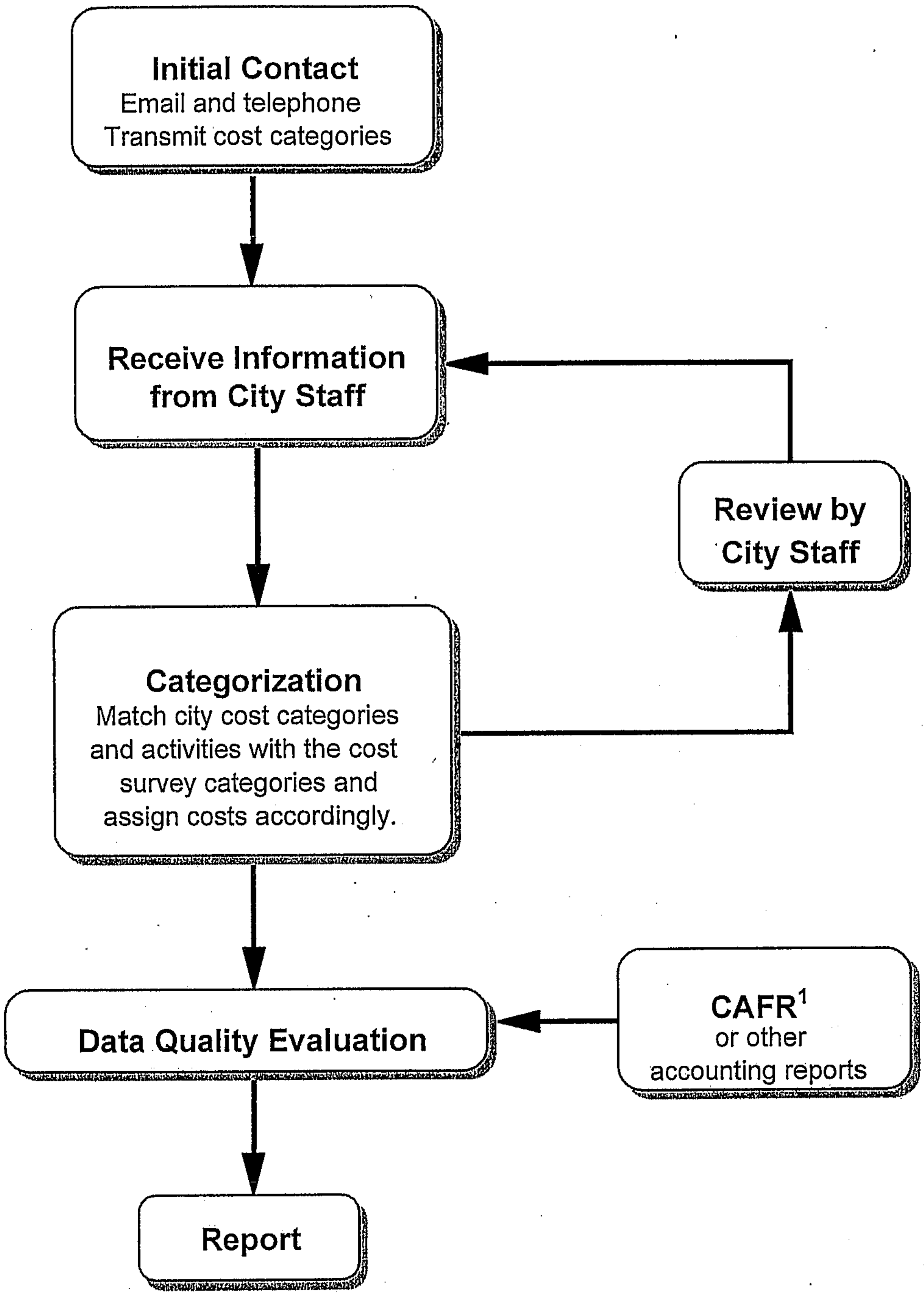
**Cost Category: Construction Site Stormwater Runoff Control[1]**

| Activity Names | External Contract | Relation to Permit[2] | Dollar Amount | Activity Statistics | Notes or Units | |
|---|---|---|---|---|---|---|
| *Activity 1* | | | | | | |
| *Activity 2* | | | | | | |
| *Activity 3* | | | | | | |

1. This example format was repeated within the table for the other cost categories.
2. This column indicates whether required activities were being performed prior to stormwater permits. In some cases activities were enhanced due to permit requirements.

Information was also collected on cost factors that might explain observed differences in costs. These factors were used to "normalize" costs by dividing the cost by the cost factors (activity statistics). Some cost factors were physical characteristics such as population or area. These were collected from census sources, city websites, and through personal communication. Others cost factors, such as number of construction site inspections, reflected stormwater program activities. Cost factors specific to individual activities or cost categories were found in the annual stormwater reports or reported in personal communications from city staff. Identical cost factors were not available for every city because cities often tracked accomplishments differently. For example, one city counted miles of drainage channel cleaned while another measured the weight of trash and debris removed during channel cleaning. As with the costs, the activity statistics were verified by city staff before being entered into tables similar to Table 2-1 under the "Activity Statistics" column.

The TAG suggested that certain fines and penalties from enforcement of ordinances relating to stormwater compliance are available to offset the cost of stormwater programs. Examples include parking tickets to accommodate street sweeping, fines for littering, construction practice violations, commercial facility operations, etc. The net revenue associated with enforcement of city ordinances that support stormwater activities was not available, partly because the cost of enforcement and penalty collection by the municipalities for stormwater violations is not known. Regardless, this does not change the cost of compliance; enforcement only seeks to identify alternative funding sources.




1. CAFR: Comprehensive Annual Financial Report

**Figure 2-2. Data Collection Methodology Flow Chart**

## 2.6 DATA QUALITY EVALUATION

After data collection, an assessment was made to assign an appropriate level of confidence in the data. The following confidence levels and criteria were used:

**High** – Costs were submitted in the form of reports generated by city accounting systems.

**Moderately High** – Costs were submitted in spreadsheets or other written form and could be checked against stormwater cost entries in the city's Comprehensive Annual Financial Report[4] (CAFR), or other accounting system reports. If a city has established a fund to account for stormwater related financial transactions, confidence was determined by comparing the cost figures found in the CAFR (or accounting system reports) and the data submitted by city stormwater staff. The costs reported in the CAFR should not be less than the staff-reported costs because the CAFR may include costs for stormwater activities not required for permit compliance. If costs submitted by stormwater staff were higher than reported CAFR costs, the inconsistency reduces the level of confidence in the data and casts doubt on the accuracy of the submitted costs.

**Moderate** – Costs were submitted in spreadsheets or other written form, but comparisons with CAFR stormwater funds or other accounting system reports could not be made.

**Low** – Costs were submitted verbally through personal communication or major costs for required programs were not available or estimated.

The goal of the data evaluation process was to assign a single confidence level to a city's overall data set. In most cases all of the data submitted by city staff received the same level of confidence because the sources were similar in nature. Where there were differences in data quality because of different data sources, the overall quality was based on the quality of the data representing the majority of the costs. A judgment was also made on the completeness of the data. For example, if major costs are missing, the confidence would be low even though the quality of the data submitted might be high. A commentary on data quality is included in the report sections corresponding to each of the cities surveyed.

## 2.7 INHERENT LIMITATIONS

As in all cost surveys, this study contains some inherent limitations. The most important of these is the almost complete dependence by the study team on the city staff members to assure the accuracy and completeness of the data provided. While some checks were made against alternate sources (e.g., the CAFRs) and common sense, it was outside the scope of this project for the study team to independently check the quality of each city's stormwater accounting information. Errors can creep into any exercise of this kind. Inherent in the process of recording data are data entry errors such as mistyped numbers. Though unintentional, these errors are

[4] A CAFR is an annual report provides information regarding all funds and account groups under the jurisdiction of a government reporting entity.

sometimes not identified and resolved. Another potential source of error is an incomplete record. Sometimes things are forgotten and overall data quality suffers.

The study team thanks the staff members of the participating cities for their efforts to assure that the data provided are as correct and complete as possible. What errors may have crept into the data are certainly unintentional, and are not believed to be large enough to affect the major findings of the study.

## 2.8 DATA COMPARISONS TO OTHER STUDIES

A review of literature revealed several sources of cost information throughout the United States. The primary sources reviewed were the Rouge River Watershed project in Michigan, the National Association of Flood and Stormwater Management Agencies (NAFSMA) survey of Phase II municipalities, and the USEPA review of Phase I costs (USEPA, 2004). These costs are discussed in Section 9.6.

The city of Corona is a moderately-sized city located inland in southern California with a population of 124,966 (www.census.gov). It is traditionally an agricultural city. The city is in the Santa Ana River watershed at the junction of State Route 91 and Interstate 15. The stormwater program is coordinated by personnel from the Department of Public Works. Descriptive characteristics for Corona are shown in Table 3-1. Primary personal communication was with Michele Colbert from the city of Corona. The city of Corona costs for 2002/2003 were for complying with their 2002 stormwater permit (RWQCB, Santa Ana, 2002).

**Table 3-1. Select Characteristics of the City of Corona**

| Description | Characteristic | Reference |
|---|---|---|
| Mean Income Per Person, $ | 21,001 | www.census.gov |
| Area, (sq. miles) | 35 | www.census.gov |
| Population | 124,966 | www.census.gov |
| Curb Miles Swept | 20,877 | Colbert, pers. comm., 3/12/04 |
| Active Construction Sites | 41 | Colbert, pers. comm., 3/12/04 |
| Industrial and Commercial Sites | 3,050 | Colbert, pers. comm., 3/12/04 |
| Households | 39,271 | www.census.gov |
| City Actual General Fund Revenue, $ | 78,413,063 | Corona, 2003a. |
| Annual Rainfall (cm) | 29 | www.wrcc.dri.edu |
| Years Since Incorporation | 108 | www.ci.corona.ca.us |

## 3.1 DATA SOURCES

The following describes the information available from the data sources.

*Cost Spreadsheets Submitted by City Staff*

A spreadsheet was provided from the city of Corona, which included labor and direct cost information for their stormwater program broken down into different categories by activity (Appendix A, Table A-2). This spreadsheet contained the majority of the city's stormwater program cost. Also, spreadsheets containing cost and other data were submitted for street sweeping and hazardous materials pick-up such as spills from vehicles involved in accidents. (Appendix A, Tables A-10 and A-11).

*City of Corona Santa Ana Watershed Annual Reporting Forms 2002/03*

This report provided activity statistics (e.g. curb miles swept) for various city stormwater programs. These statistics were used to normalize costs to allow comparison with other cities.

*Personal Communication: Interviews, Phone Calls, E-Mail*

Personal communication with city of Corona staff provided additional stormwater program costs that augmented the data submitted in their cost spreadsheet. Through personal communication, city staff elaborated on what was accomplished for each cost submitted in their spreadsheet and commented on the allocation of costs among the cost survey categories.

*Comprehensive Annual Financial Report (CAFR) 2002/03*

The city of Corona has not established a fund to account for overall stormwater transactions, therefore no cost comparisons were made to CAFR figures.

*Santa Ana Regional Drainage Area Management Plan (SAR-DAMP) 1993*

This document describes the overall stormwater management strategies planned by the municipalities in the Santa Ana drainage area of Riverside County (Corona SAR-DAMP). While no cost figures were obtained from this document, it was used to verify that an activity was required by the permit.

## 3.2 COST DATA SUMMARY

Table 3-2 summarizes the costs for each survey category. Figure 3-1 shows the relative distribution of costs among the categories. Stormwater staff labor costs were not distributed among survey categories, but were 100 percent allocated to the Overall Stormwater Program Management category. This will make Overall Stormwater Program Management costs appear higher compared to cities that allocate stormwater staff costs to their various programs. According to city staff, the industrial stormwater program is just getting started so costs of that program probably do not represent a mature industrial program (Colbert, personal communication, 3/12/04).

**Table 3-2. City of Corona Cost Assigned to Cost Survey Categories**

| *Cost Survey Category* | *Costs ($)* |
|---|---|
| Construction Site Stormwater Runoff Control | 53,382 |
| Illicit Discharge Detection and Elimination | 20,628 |
| Industrial and Commercial Management Programs | 89,916 |
| Overall Stormwater Program Management | 317,800 |
| Pollution Prevention and Good Housekeeping for Municipal Operations | 720,222 |
| Post Construction Stormwater Management in New Development and Redevelopment | 13,509 |
| Public Education, Outreach, Involvement, and Participation | 28,409 |
| Water Quality Monitoring | 7,000 |
| Watershed Management | 0 |
| **Total** | **1,250,866** |

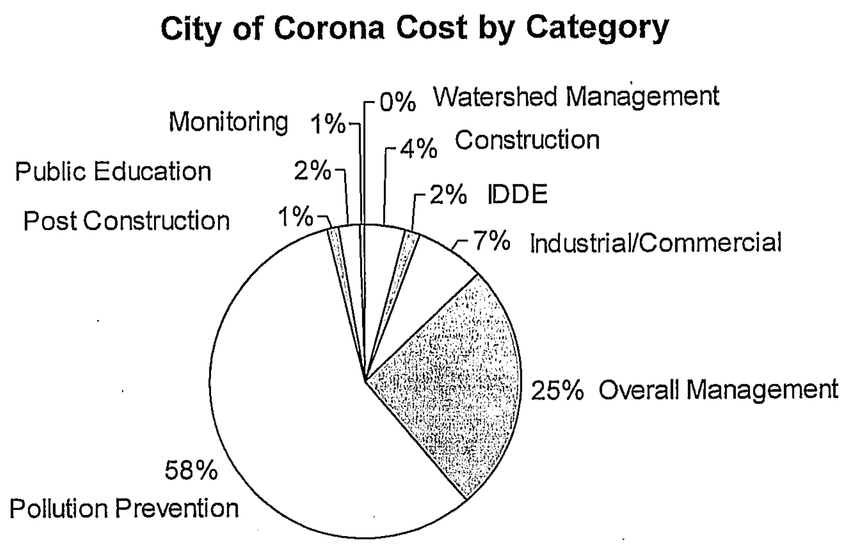



**Figure 3-1. Distribution of Corona Stormwater Costs among the Cost Survey Categories.**

### 3.2.1 Discussion of Costs for Each Survey Category

This section presents the major activities for each cost survey category. Further cost breakdown and calculations for each survey category are included in Appendix A. The costs for each survey category are discussed in this section in alphabetical order.

*Construction Site Stormwater Runoff Control*

The construction program cost was $53,382, which was 4 percent of total stormwater cost. The construction program oversaw 41 active construction sites and performed 564 inspections (Colbert, personal communication, 3/12/04). Including the cost for vehicles, phone usage, training, and stormwater staff labor, the average cost was $95 per inspection and $1,302 per active construction site.

*Illicit Discharge Detection and Elimination (IDDE)*

The IDDE program cost was $20,628, which was 2 percent of total stormwater cost. The largest cost attributed to this program was for the stormwater share of inspections performed by wastewater staff. The average cost per inspection was $157. Also, new development illicit connection inspections were conducted, which added to the cost of this program (Colbert, personal communication, 3/12/04).

*Industrial and Commercial Management Programs*

The industrial and commercial program cost was $89,916, which was 7 percent of total stormwater cost. The industrial program had 600 inspections at an average cost of $134 per inspection.

*Overall Stormwater Program Management*

The overall management program cost was $317,800, which was 25 percent of total stormwater cost. The city was unable to distribute the staff cost among the cost survey categories so all of the stormwater staff cost was assigned to this category. Administrative service charges account for 25 percent of this category's cost. The staff costs represent approximately 62 percent of the costs assigned to this category and 16 percent of total stormwater cost. The remaining 23 percent are for office supplies, reporting, and NPDES fee.

*Pollution Prevention and Good Housekeeping for Municipal Operations*

The municipal operations program cost was $720,222, which was 58 percent of total stormwater cost. The two primary activities in this category were street sweeping and drain line/channel cleaning. The average cost was $20 per curb mile swept and $8 per linear foot of drain lines and channels cleaned. Street sweeping and drain line and channel cleaning account for 33 percent and 20 percent of total stormwater cost respectively. City staff labor associated with these activities is reported in this category.

*Post Construction Stormwater Management in New Development and Redevelopment*

The post construction program cost was $13,509, which was 1 percent of total stormwater cost. Post construction cost was primarily for professional consulting services for BMP selection. Also, installation and maintenance of 8 storm drain inlet inserts cost $4,500, averaging $562 per insert per year.

*Public Education, Outreach, Involvement, and Participation*

The public education program cost was $28,409, which was 2 percent of total stormwater cost. Public education and outreach activities often incorporated public involvement and participation activities. This made differentiating cost between the categories impractical. Because of this, the two programs were combined.

*Water Quality Monitoring*

The monitoring program cost was $7,000, which was 0.6 percent of total stormwater cost. This cost was associated with the illicit discharge detection and elimination program.

*Watershed Management*

The city of Corona did not allocate any cost to this category. The effort was captured under other programs such as Overall Stormwater Program Management.

## 3.3 CONFIDENCE IN THE DATA

For the city of Corona, confidence in the data was moderate because most of the cost data submitted was via spreadsheets built, maintained, and updated by the city. However, as with most of the cities selected, the program costs provided could not be verified by city accounting system reports.

Since the city did not have a fund in place to account for overall stormwater related transactions, comparison of stormwater costs submitted by city staff with CAFR cost figures was not possible. This limited the level of confidence in the data to 'moderate.'

The city of Encinitas represents the smallest city selected for the survey with a population of just over 58,000 (www.census.gov). The area of the city is about 20 square miles and is located 25 miles north San Diego. Encinitas is situated along six miles of rugged coastline; characterized by beaches, cliffs, and rolling hills (www.ci.encinitas.ca.us). The stormwater program is coordinated by the Engineering Services Department. Descriptive characteristics for the Encinitas are shown in Table 4-1. Primary personal communication was with Kathy Weldon from the city of Encinitas and Meleah Ashford of Ashford Engineering. The city of Encinitas costs for 2002/2003 were for complying with their 2001 stormwater permit (RWQCB, San Diego, 2001).

**Table 4-1. Select Characteristics of the City of Encinitas**

| Description | Characteristic | Reference |
|---|---|---|
| Mean Income Per Person, $ | 34,336 | www.census.gov |
| Area (sq. miles) | 20 | www.census.gov |
| Population | 58,014 | www.census.gov |
| Curb Miles Swept | 5,832 | Encinitas, 2003b |
| Active Construction Sites | 40 | Encinitas, 2003b |
| Industrial and Commercial Sites | 417 | Encinitas, 2003b, Weldon, pers. comm., 4/2/04 |
| Households | 23,843 | www.census.gov |
| City Actual General Fund Revenue, $ | 42,592,755 | Encinitas, 2003a |
| Annual Rainfall (cm)* | 26 | www.wrcc.dri.edu |
| Years Since Incorporation | 20 | www.ci.encinitas.ca.us |
| *Rainfall for Oceanside Marina was used. | | |

## 4.1 DATA SOURCES

The following describes the information available from the data sources.

*Cost Spreadsheets Submitted by City Staff*

A spreadsheet was provided by the city of Encinitas that included cost information broken down by activity (Appendix B, Table B-2). The city also submitted another spreadsheet, which allocated the labor, supplies, travel, equipment, and vehicle cost to each stormwater program (Appendix B, Table B-3). The remaining cost data submitted was for public works department costs related to stormwater activities (Appendix B, Table B-4).

*Jurisdictional Urban Runoff Management Program (JURMP) Annual Report, FY 2002-2003*

This report provided descriptions of the activities and accomplishments of the city's stormwater program (Encinitas, 2003b). Activity statistics (e.g. number of industrial inspections) were provided in this report as well. Stormwater costs were normalized by these statistics. While no cost figures were obtained from this document, it was used to verify that an activity was required for compliance with the permit.

*Personal Communication: Interviews, Phone Calls, E-mail*

Personal communication with the city of Encinitas staff provided additional stormwater program costs that augmented the data submitted in their cost spreadsheet. These costs were for stormwater activities performed by the department of public works. They also provided allocations of labor, supplies, travel, equipment, and vehicle to cost survey categories based on estimated percentages. Also, city staff elaborated on what was accomplished for each cost submitted in their spreadsheet and commented on the allocation of costs among the cost survey categories.

*Comprehensive Annual Financial Report (CAFR) 2002/03*

The city of Encinitas has not established a fund to account for overall stormwater transactions, so no comparisons on cost were made to CAFR figures. During fiscal year 2003/04, the city has since created such a fund (Ashford, personal communication, 4/2/04).

## 4.2 COST DATA SUMMARY

Table 4-2 summarizes the costs for each survey category. Figure 4-1 shows the relative distribution of costs among the categories. The costs in Table 4-2 include an allocation of stormwater staff time used to develop, oversee, and, in some cases, implement activities within each program.

The backup calculations and source data for these costs are presented and discussed in Appendix B.

**Table 4-2. City of Encinitas Cost Assigned to Cost Survey Categories**

| Cost Survey Category | Costs ($) |
|---|---|
| Construction Site Stormwater Runoff Control | 169,751 |
| Illicit Discharge Detection and Elimination | 49,378 |
| Industrial and Commercial Management Programs | 65,596 |
| Overall Stormwater Program Management | 128,159 |
| Pollution Prevention and Good Housekeeping for Municipal Operations | 528,252 |
| Post Construction Water Management in New Development and Redevelopment | 15,344 |
| Public Education, Outreach, Involvement, and Participation | 41,898 |
| Water Quality Monitoring | 76,262 |
| Watershed Management | 12,400 |
| **Total** | **1,087,038** |

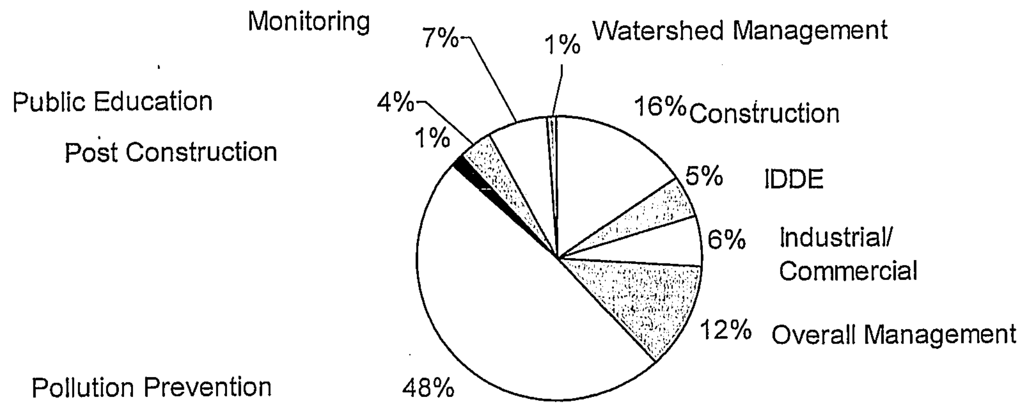



**Figure 4-1. Distribution of Encinitas Stormwater Costs Among the Cost Survey Categories.**

### 4.2.1 Discussion of Costs for Each Survey Category

Cost breakdown and calculations for each survey category are found in Appendix B, Table B-1. The costs for each survey category are discussed in this section.

*Construction Site Stormwater Runoff Control*

The construction program cost was $169,751, which was 16 percent of total stormwater cost. The construction program oversaw 40 active construction sites and performed 401 inspections (Encinitas, 2003b). Including the cost of stormwater staff for oversight and follow-up activities, the average cost was $423 per inspection and $4,244 per active construction site. The normalized cost for Encinitas may be high compared to other cities because the cost includes non-inspection activities such as contractor and inspector training, wet weather monitoring, and BMP manual updating. Stormwater staff also reviewed five SWPPPs, performed general enforcement, issued 13 notices of violation, updated the city BMP manual, educated and trained engineering inspectors with regard to stormwater management and BMP implementation, monitored weather patterns and storms in the Pacific through the National Weather Service, conducted construction education, disseminated brochures and mailings, and held a construction workshop (City of Encinitas, 2003b).

*Illicit Discharge Detection and Elimination*

The IDDE program cost was $49,378, which was 4 percent of total stormwater cost. The IDDE program conducted 172 education, enforcement, and/or clean-up activities. Using overall IDDE



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cost, the average cost per activity was $287. From informal visual inspections, city staff received 76 "complaints," and another 96 complaints were received via the city's stormwater hotline.

*Industrial and Commercial Management Programs*

The industrial and commercial program cost was $65,596, which was 6 percent of total stormwater cost. This program had 266 inspections at an average cost of $247 per inspection. The normalized cost for Encinitas may be high compared to other cities because the cost includes non-inspection activities such as website updating, facility inventory, education, and enforcement actions (City of Encinitas, 2003b). The city has three industrial sites and 348 commercial sites. Stormwater staff updated the commercial facility inventory, provided BMP manuals and guidance, educated facility staff in regard to stormwater requirements and minimum BMPs, developed a grease program, and issued several enforcement actions (City of Encinitas, 2003b).

*Overall Stormwater Program Management*

The overall management program cost was $128,159, which was 12 percent of total stormwater cost. Developing a "clean water fee" cost $35,000 (Weldon, personal communication, 4/2/04). This fee pays for stormwater costs and is similar to stormwater fees assessed by other cities. This cost accounts for approximately 27 percent of this category's cost. The other activities in this program were annual reporting and legal support for developing ordinances and plaintiff attorney fees. Costs in this category identified as possibly one-time were for the stormwater fee development, legal fees (ordinances and plaintiff attorneys), and grant writing.

*Pollution Prevention and Good Housekeeping for Municipal Operations*

The municipal operations program cost was $528,252, which was 49 percent of total stormwater cost. This category had three primary public works activities: cleaning sumps, inlets, and manholes; street sweeping; and cleaning drain lines and channels. Activity statistics were only available for street sweeping which was contracted out with minimal oversight (Weldon, personal communication, 4/2/04). The average cost was $20 per curb mile swept. The street sweeping cost is about 11 percent of total stormwater cost. Street sweeping cost does not include labor of the stormwater staff. This was because stormwater staff time was allocated to all municipal operations for stormwater and not to individual activities (e.g. street sweeping vs. channel cleaning). Other activities included in this program were trash pick-up, sediment disposal, and consulting services for oversight, strategic planning, and management.

*Post Construction Stormwater Management in New Development and Redevelopment*

The post construction program cost was $15,344, which was 1 percent of total stormwater cost. Post-construction cost was primarily for consulting and oversight of a special project to treat discharge to Moonlight Beach for bacteria. Also, installation and maintenance of 16 storm drain inserts cost $1,908, averaging $119 per insert per year. The cost associated with the "Moonlight Beach" project was possibly a one-time cost.

*Public Education, Outreach, Involvement, and Participation*

The public education program cost was $41,898, which was 4 percent of total stormwater cost. Public education and outreach activities often incorporated public involvement and participation activities. This made differentiating cost between the categories impractical. Because of this, the two programs were combined. The city of Encinitas had three watershed and beach clean-up activities (City of Encinitas, 2003b). Because the cost of outreach was not available separately and impression statistics were not available, outreach costs were not normalized.

*Water Quality Monitoring*

The monitoring program cost was $76,262, which was 7 percent of total stormwater cost. The cost was for collection, analysis, and contractor oversight of 48 dry weather bacteria samples (Weldon, personal communication, 4/2/04).

*Watershed Management*

The cost of this category was $12,400, which was 1 percent of total stormwater cost. These costs were for developing a one time watershed plan and participating in and hosting regional watershed meetings and workshops (Weldon, personal communication, 4/2/04).

## 4.3 CONFIDENCE IN THE DATA

For the city of Encinitas, confidence in the data was moderately high. This was because only a few cost figures submitted were verbal estimates without backup. Most of the cost data submitted was via spreadsheets built, maintained, and updated by the city. However, as with most of the cities selected, the program costs were provided but could not be verified by city accounting system reports.

For the fiscal year 2002/03, the city did not have a fund in place to account for overall stormwater related transactions. As such, comparison of stormwater costs submitted by city staff with CAFR cost figures was not possible, which did not allow for a higher level of confidence in the data.

Fremont was the third largest city selected and has a population of about 203,000 (www.census.gov). The city is located in Alameda County on the southeast side of the San Francisco Bay between San Jose and Oakland. The stormwater program is coordinated by the Environmental Services Department. Descriptive characteristics for Fremont are shown in Table 5-1. Primary personal communication was with Barbara Silva from the city of Fremont. The FCMA costs for 2002/2003 were for complying with their 2003 stormwater permit (RWQCB, San Francisco Bay, 2003).

**Table 5-1. Select Characteristics of the City of Fremont**

| Description | Characteristic | Reference |
|---|---|---|
| Mean Income Per Person, $ | 31,411 | www.census.gov |
| Area, (sq. miles) | 97 | Silva, pers. comm., 4/5/04 |
| Population | 203,413 | www.census.gov |
| Curb Miles Swept | 31,405 | Silva, pers. comm., 9/22/04 |
| Active Construction Sites | 24 | Silva, pers. comm., 4/5/04 |
| Industrial and Commercial Sites | 1,028 | Silva, pers. comm., 4/5/04 |
| Households | 69,452 | www.census.gov |
| City Actual General Fund Revenue, $ | 98,456,011 | Fremont, 2003a |
| Annual Rainfall (cm) | 37 | www.wrcc.dri.edu |
| Years Since Incorporation | 48 | www.ci.fremont.ca.us |

## 5.1 DATA SOURCES

The following describes the information available from the data sources.

*Cost Spreadsheets Submitted by City Staff*

The city of Fremont provided a cost spreadsheet that included labor and cost figures for stormwater activities (Appendix C, Table C-2). A further breakdown of one of these cost figures was also provided (Appendix C, Table C-3). A further breakdown of Union Sanitation District[5] (USD) cost is presented in Appendix C, Table C-4. Appendix Table C-5 presents a breakdown of city of Fremont contributions to the Alameda Countywide Clean Water Program (ACCWP).

*Alameda Countywide Clean Water Program Fiscal Year 2002/03 Annual Report*

The city of Fremont is a member of the ACCWP, so the 2002/03 Annual Report was consulted to obtain activity statistics, descriptions of activities, and accomplishments specifically pertaining

[5] The Union Sanitation District is a special district that provides wastewater collection, treatment and disposal services to the residents and businesses of the city of Fremont, Newark and Union City, in Southern Alameda County in California (www.unionsanitary.com).

to the city of Fremont. As with other cities where relevant activity statistics were available, cost normalization was performed.

*Personal Communication: Phone Calls, E-mail*

Through personal communication, city staff provided detailed information regarding cost figures. City staff elaborated on what was accomplished for each cost submitted in their spreadsheet and commented on the allocation of costs among the cost survey categories.

*Comprehensive Annual Financial Report (CAFR) 2002/03*

During the 2002/03 fiscal year, the city of Fremont had a fund in place to account for overall stormwater related transactions. This fund is called the "Urban Runoff/Clean Water" fund (Fremont, 2003a). The cost figures in this fund were used for comparison purposes with costs submitted by city stormwater staff.

*Alameda Countywide Clean Water Program, SWMP, July 2001-June 2008*

The SWMP provided information regarding the structure, accomplishments, and recent developments of the program. It also gave information regarding objectives and tasks of each program component and specific tasks that the member agencies are required to perform (Fremont, 2003c). While no cost figures were obtained from this document, it was used to verify that an activity was required for compliance with the permit.

## 5.2 COST DATA SUMMARY

Table 5-2 summarizes the costs for each survey category. Figure 5-1 shows the relative distribution of costs among the categories. Stormwater staff labor costs for the city of Fremont were not distributed among survey categories, but were allocated to Overall Stormwater Program Management. This will make the costs in this category appear higher compared to cities that allocate stormwater staff costs to their various programs. Survey categories (excluding Overall Stormwater Program Management) that include costs or discussion in regard to "stormwater staff labor" only concerns ACCWP labor cost allocated to the city of Fremont. Fremont funded the USD to accomplish portions of the IDDE, industrial/commercial, construction, overall management, and public education programs.

**Table 5-2. City of Fremont Cost Assigned to Cost Survey Categories**

| Cost Survey Category | Costs ($) |
|---|---|
| Construction Site Stormwater Runoff Control | 17,715 |
| Illicit Discharge Detection and Elimination (IDDE) | 5,917 |
| Industrial and Commercial Management Programs | 210,027 |
| Overall Stormwater Program Management | 453,872 |
| Pollution Prevention and Good Housekeeping for Municipal Operations | 2,128,175 |
| Post Construction Stormwater Management in New Development and Redevelopment | 35,083 |
| Public Education, Outreach, Involvement, and Participation | 101,717 |
| Water Quality Monitoring | 131,326 |
| Watershed Management | 17,610 |
| **Total** | **3,101,442** |

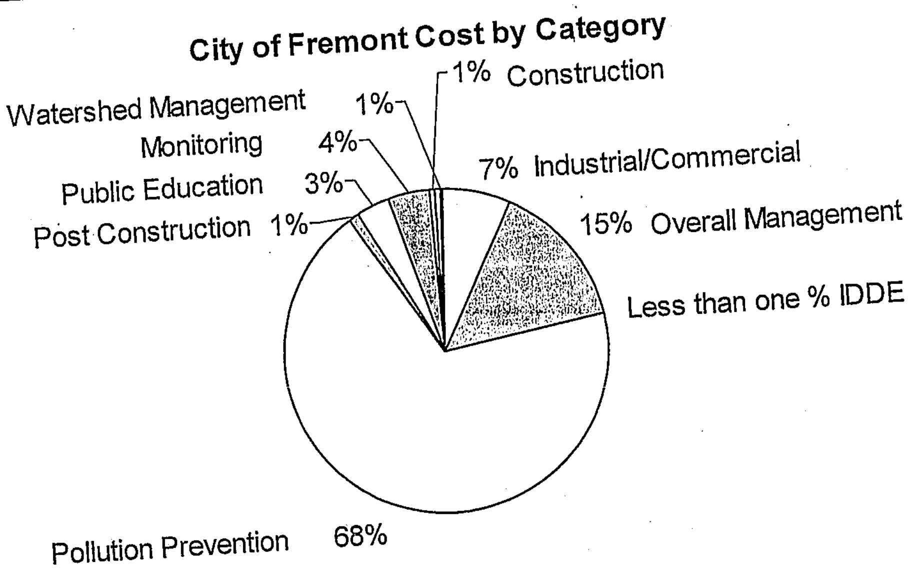


**Figure 5-1. Distribution of Fremont Stormwater Costs Among the Cost Survey Categories.**

### 5.2.1 Discussion of Costs for Each Survey Category

Cost breakdown and calculations for each survey category are found in Appendix C, Table C-1. The costs for each survey category are discussed in this section.

*Construction Site Stormwater Runoff Control*

The construction program (performed by USD), cost was $17,715, which was 1 percent of total stormwater cost. The construction program oversaw 24 active construction sites equal to or greater than five acres (Silva, personal communication, 4/5/04). All of the cost for the program was attributable to inspections (Silva, personal communication, 4/5/04). The program cost,



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normalized by construction sites, was $738 per active construction site greater than or equal to five acres.

*Illicit Discharge Detection and Elimination*

The IDDE program cost was $5,917, which was less than one percent of total stormwater cost. Most of the cost (86 percent) was for assistance to eliminate non-stormwater discharges and reporting. Stormwater staff labor cost represented the remaining 14 percent.

*Industrial and Commercial Management Programs*

The industrial and commercial program cost was $210,027, which was 7 percent of total stormwater cost. This program was performed by the USD, who performed 482 inspections with 91 follow-up actions of which 81 were enforcement actions. Not including documentation cost, the cost per inspection was $334.

*Overall Stormwater Management Program*

The overall management program cost was $453,872, which was 15 percent of total stormwater cost. Stormwater staff labor costs are included in this category. The labor costs (including overhead) represent about 69 percent of the cost attributed to this program. The other costs were for administrative services and supplies, permit fees, informational systems, and USD services.

*Pollution Prevention and Good Housekeeping for Municipal Operations*

The municipal operations program cost was $2,128,175, which was 69 percent of total stormwater cost. The two primary activities of this category were street sweeping, and litter and debris removal. The average cost was $61 per curb mile swept. For this category, street sweeping accounted for approximately 90 percent of the cost and 9 percent was attributable to litter debris and removal. Other activities performed by the city included cleaning drain lines and channels, inlets, cross culverts, and conduits, but costs were not available for these activities.

*Post Construction Stormwater Management in New Development and Redevelopment*

The post construction program cost was $35,083, which was 1 percent of total stormwater cost. This cost was for engineering, planning, and other city staff to research, track, and report information for the annual stormwater report. It was also for task force meetings to develop strategies for compliance with their permit regarding new development and redevelopment, brochure printing, and stormwater staff labor.

*Public Education, Outreach, Involvement, and Participation*

The public education program cost was $101,717, which was 3 percent of total stormwater cost. Program activities included production and distribution of citywide newsletters, 28 school outreach presentations, stormwater staff participation in public events, and distribution of brochures and fliers (Fremont, 2003b). USD was funded $25,897 to provide additional public education outreach services. Outreach materials promote an Integrated Pest Management program that provided businesses and nurseries with shelf displays and fact sheets.

*Water Quality Monitoring*

The monitoring program cost was $131,326, which was 4 percent of total stormwater cost. This cost was for multiple water quality sampling at two locations. Both chronic and acute toxicity tests were performed (Silva, personal communication, 4/5/04).

*Watershed Management*

The watershed management program cost was $17,610, which was 1 percent of total stormwater cost. Costs in this category were for developing a watershed study framework, assessment of pilot project activities, and stormwater staff labor (including overhead).

## 5.3 CONFIDENCE IN THE DATA

For the city of Fremont, confidence in the data was moderately high. Most of the cost data submitted was via spreadsheets built, maintained, and updated by the city. Approximately one-third of the city costs could be corroborated by the 2003/2004 CAFR figures.

The city of Fremont had a fund (Urban Runoff/Clean Water) presented in the CAFR that accounted for stormwater expenditures except street sweeping and litter/debris removal (Cote, 2004). Total expenditures and transfers out for the Urban Runoff/Clean Water fund were $1,234,790. Total stormwater costs submitted by city staff were $3,101,442 but this included $2,115,000 in street sweeping and litter/debris removal costs (Cote, 2004). Subtracting out $2,115,000 leaves $986,442 in stormwater costs compared to the $1,234,790 in the Urban Runoff/Clean Water fund. Because of water conveyance projects, it is expected that compliance costs would be less than this fund reports. The $2,115,000 could not be verified by CAFR figures because it was financed out of larger funds that did not have available breakdown. This cost was about 68 percent of the total stormwater cost.

The Fresno-Clovis Metropolitan Area (FCMA) has a population of 778,000, but a population of nearly 695,000 is used for comparison of normalized costs because this is approximately the population under the jurisdiction of the Fresno Metropolitan Flood Control District (FMFCD), which is the lead agency for compliance efforts. The FCMA is the largest area considered in this cost survey. Fresno is located in the San Joaquin Valley near the Sierra Nevada. Surrounded by agricultural land, the area includes the city of Fresno, the city of Clovis, and other metropolitan areas of Fresno County. The stormwater program is coordinated by the Environmental Services Department. Descriptive characteristics for FCMA and the other agencies, excluding California State University, Fresno (CSUF) are shown in Table 6-1. Primary personal communication was with Daniel Rourke and David Pomaville from the FMFCD. The FCMA costs for 2002/2003 were for complying with their 2002 stormwater permit (RWQCB, Central Valley, 2002a).

**Table 6-1. Select Characteristics of the Fresno Metropolitan Area**

| Description | Fresno-Clovis Area | City of Clovis | County of Fresno | City of Fresno | Reference |
|---|---|---|---|---|---|
| Mean Income Per Person, $ | * | 18,690 | 15,495 | 15,010 | www.census.gov |
| Area, (sq. miles) | * | 17 | 6,017 | 105 | www.census.gov |
| Population | 561,120 | 68,468 | 65,000*** | 427,652 | www.fresnofloodcontrol.org |
| Curb Miles Swept | 142,411 | 47,430 | 21 | 94,495 | FMFCD, 2003b |
| Active Construction Sites | N/A | N/A | N/A | N/A | N/A |
| Industrial and Commercial Sites | N/A | N/A | N/A | N/A | N/A |
| Households** | 195,311 | 25,250 | 21,036 | 149,025 | www.census.gov |
| City Actual General Fund Revenue, $ | 216,089,323 | 37,707,095 | 0 | 178,382,228 | Respective CAFRs |
| Annual Rainfall (cm) | 28 | 28 | 28 | 28 | www.wrcc.dri.edu |
| Years Since Incorporation | 119 | 92 | N/A | 119 | www.ci.fresno.ca.us |

* Approximately equal to county.
**County of Fresno number of households obtained by dividing the population covered by the stormwater permit by the average number of households in the county according to census 2000. Population provided via personal communication (Pomaville, 6/10/04).
*** County population is only that portion outside the cities but also covered by the FMFCD.

## 6.1 DATA SOURCES

The following describes the information available from the data sources.

*Cost Spreadsheets Submitted by City Staff*

The FMFCD provided a spreadsheet generated from an accounting system report. This detailed spreadsheet provided individual expenditures for stormwater except for labor and office supplies (Appendix D, Table D-7).

*Fresno-Clovis Storm Water Quality Management Program, Annual Report FY 2002/2003*

This report provided descriptions of the activities and accomplishments of the stormwater program. Activity statistics (e.g. number of construction site inspections) were provided in this report, but in most cases numbers were not available for each agency.

*Fresno-Clovis Storm Water Quality Management Program (SWQMP), February 1999*

The SWQMP presents information regarding objectives and tasks of each program component and specific tasks that the member agencies are required to perform. The report contained budgeted costs incurred by the cities, county, and university in lieu of actual expenditures. These costs were summarized in Appendix D, Table D-3. The cost figures were budgeted amounts and not actual expenditures. The document was also used to verify that an activity was required for compliance with the permit.

*Personal Communication: Phone Calls, E-mail*

Personal communication with the FMFCD staff provided additional stormwater program costs that augmented the data submitted in their cost spreadsheet. These costs were for labor, office supplies, and street sweeping (Appendix Table D-8). They also provided advice on how to allocate the submitted costs to the cost survey categories. FMFCD staff also advised on where the best available costs were compiled for the other agencies.

*Comprehensive Annual Financial Report (CAFR) 2002/03 for the FMFCD, City of Clovis, City of Fresno, and County of Fresno*

Except for the FMFCD, the Fresno area agencies had not established a fund to account for overall stormwater transactions, so no comparisons on cost were made to CAFR figures. The CAFR figures were used to determine the general fund revenue, which is considered a potential cost factor.

## 6.2 COST DATA SUMMARY

Table 6-2 summarizes the stormwater program costs for each cost survey category. Figure 6-1 shows the relative distribution of costs among the categories. Labor cost for the FMFCD staff to develop, oversee, and administer these programs was allocated to the Overall Stormwater Program Management category. The labor costs for the other agencies were allocated to the cost categories.

**Table 6-2. Fresno-Clovis Metropolitan Area Cost Assigned to Cost Survey Categories**

| Cost Survey Category | Costs ($) |
|---|---|
| Construction Site Stormwater Runoff Control | 81,800 |
| Illicit Discharge Detection and Elimination (IDDE) | 13,176 |
| Industrial and Commercial Management Programs | 47,780 |
| Overall Stormwater Program Management | 570,495 |
| Pollution Prevention and Good Housekeeping for Municipal Operations | 2,240,605 |
| Post Construction Stormwater Management in New Development and Redevelopment | 57,539 |
| Public Education, Outreach, Involvement, and Participation | 210,716 |
| Water Quality Monitoring | 252,918 |
| Watershed Management | 0 |
| **Total** | **3,475,029** |

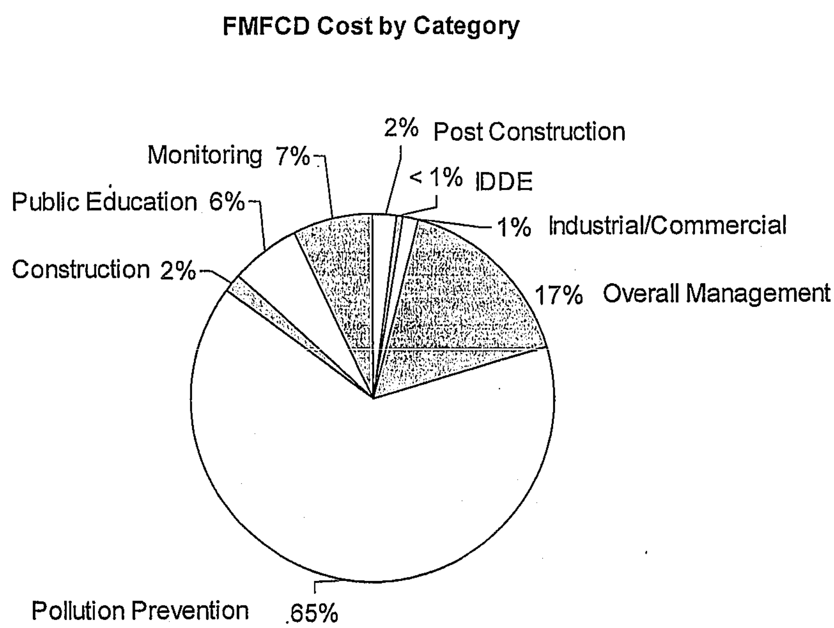


**Figure 6-1. Distribution of Fresno-Clovis Metro Area Stormwater Costs Among the Cost Survey Categories**

### 6.2.1 Discussion of Costs for Each Category

Cost breakdown and calculations for each survey category are found in Appendix D, Table D-1. The costs for each survey category are discussed in this section.

*Construction Site Stormwater Runoff Control*

The construction program cost was $81,800, which was 2 percent of total stormwater cost. The annual stormwater report did not contain the number of inspections for the city of Fresno, so cost could not be normalized by this factor. The number of construction sites was only tracked for the FMFCD so this factor was not used. (FMFCD, 2003b).

*Illicit Discharge Detection and Elimination (IDDE)*

The IDDE program cost was $13,176, which was less than one percent of total stormwater cost. The number of inspections was not available.

*Industrial and Commercial Management Programs*

The industrial and commercial program cost was $47,480, which was 1 percent of total stormwater cost. Facilities in the Fresno-Clovis metropolitan area are primarily inspected by Fresno County hazardous waste inspectors, city of Fresno industrial wastewater inspectors, and city of Clovis fire inspectors (FMFCD, 2003b). The number of inspections was only available for the FMFCD so cost could not be normalized on this factor.

*Overall Stormwater Program Management*

The overall stormwater program management cost was $570,495, which was 16 percent of total stormwater cost. This cost includes the FMFCD staff costs for stormwater (does not include other FMFCD activities such as flood control), which accounted for 98 percent of the cost of this category. The staff costs attributed to stormwater activities were estimated as 11 percent of the total personnel expenses for the FMFCD. The same percentage was applied to obtain office administration costs (Pomaville, 2004). Other costs were for office expenses, office administration, training, and travel.

*Pollution Prevention and Good Housekeeping for Municipal Operations*

The cost of this program was $2,240,605, which was 64 percent of total stormwater cost. This includes $2,193,296 reported by the city of Clovis and city of Fresno for street sweeping 141,769 of the 142,411 curb miles swept by the agencies (FMFCD, 2003b).

*Post Construction Stormwater Management in New Development and Redevelopment*

The post construction program cost was $57,539, which was 2 percent of total stormwater cost. This cost was for contracting for maintenance of 8 basins, resulting in an average annual cost of $7,200 per basin.

*Public Education, Outreach, Involvement, and Participation*

The cost of this program was $210,716, which was 6 percent of total stormwater cost. The Public Education and Outreach category was combined with the Public Involvement and Participation category because the county of Fresno and city of Clovis costs were combined (FMFCD, 1999). There was not a consistently reported activity statistic that could be used for normalization. FCMA agencies were involved in many outreach and participation activities such as public service announcements, brochures, BMP fact sheets, volunteer stenciling, special events, articles, clean-up activities, hotline, school programs, and business outreach (FMFCD, 2003b).

*Water Quality Monitoring*

The monitoring program cost was $252,918, which was 7 percent of total stormwater cost. The program funded monitoring plan development, sample collection, analysis, reporting, and a Water Environment Research Foundation (WERF) contribution. Only FMFCD reported monitoring costs.

*Watershed Management*

The Fresno area agencies did not allocate any cost to this category. This effort was captured under other programs such as Overall Stormwater Program Management.

## 6.3 CONFIDENCE IN THE DATA

For the Fresno-Clovis metropolitan area, confidence in the data was moderate because costs for the other agencies were taken from budgeted numbers out of the SWQMP (FMFCD, 1999). Additionally, baseline labor costs for the cities and county were less than $90,000 (Appendix D, Table D-3), which is approximately the annual cost of one person (salary and overhead). It seems unreasonable that this cost sufficiently covers the pre-existing stormwater labor cost in 1999 for these entities. The street sweeping costs provided for the city of Clovis were corroborated by the city's 2002/03 CAFR within 1 percent.

Surrounded by largely agricultural land, California's capital city is located in the central valley at the conjunction of the Sacramento and American rivers. The city of Sacramento has a population just exceeding 400,000 (www.census.gov). The stormwater program is coordinated by the Department of Utilities. Descriptive characteristics for the city of Sacramento are shown in Table 7-1. Primary personal communication was with Bill Busath from the city of Sacramento. The city of Sacramento costs for 2002/2003 were for complying with their 2002 stormwater permit (RWQCB, Central Valley, 2002b).

**Table 7-1. Select Characteristics of the City of Sacramento**

| Description | Characteristic | Reference |
|---|---|---|
| Mean Income Per Person, $ | 18,721 | www.census.gov |
| Area, (sq. miles) | 99 | www.census.gov |
| Population | 407,018 | www.census.gov |
| Curb Miles Swept | 26,450 | Table E-6 |
| Active Construction Sites | 417 | Sacramento, 2003b |
| Industrial and Commercial Sites | N/A | N/A |
| Households | 163,957 | www.census.gov |
| City Actual General Fund Revenue, $ | 267,464,000 | Sacramento, 2003a |
| Annual Rainfall (cm) | 46 | www.wrcc.dri.edu |
| Years Since Incorporation | 154 | www.cityofsacramento.org |
| *Reporting these numbers started in fiscal year 2004/05 (Sacramento, 2003b) | | |

## 7.1 DATA SOURCES

The following describes the information available from the data sources.

*Cost Spreadsheets Submitted by City Staff*

The staff provided two spreadsheets, which included cost data. One spreadsheet contained direct costs while the other contained labor costs. These spreadsheets represent the entirety of the city's stormwater costs except for the verbal estimates for street sweeping and pump station cleaning activities. The direct and labor cost spreadsheets are presented in Appendix E, Tables E-2 and E-8 respectively. The labor costs as assigned to cost survey categories are presented in Table E-7.

*City of Sacramento, Stormwater Management Program, 2002/03 Annual Report*

This report provided activity statistics (e.g. curb miles swept) for various city stormwater programs. These statistics were used to normalize costs to allow comparison with other cities.

*Personal Communication: Interviews, Phone Calls, E-Mail*

Through personal communication, city staff elaborated on what was accomplished for each cost submitted in their spreadsheet and commented on the allocation of costs among the cost survey categories. Also, verbal cost estimates for street sweeping and pump station cleaning activities were provided.

*Comprehensive Annual Financial Report (CAFR) 2002/03*

During the 2002/03 fiscal year, the city of Sacramento had a fund in place to account for overall stormwater related transactions. This fund is called the "Storm Drainage" fund (Sacramento, 2003a). The cost figures in this fund were used for comparison purposes with costs submitted by city stormwater staff.

*City of Sacramento, Stormwater Quality Improvement Plan (SQIP) July 2003*

While no cost figures were obtained from this document, it was used to verify that an activity was required for compliance with the permit.

## 7.2 COST DATA SUMMARY

Table 7-2 summarizes the stormwater program costs for each cost category. Figure 7-1 shows the relative distribution of costs among the categories. These cost figures include labor costs for the stormwater staff.

**Table 7-2. City of Sacramento Cost Assigned to Cost Survey Categories**

| Cost Survey Category | Costs ($) |
|---|---|
| Construction Site Stormwater Runoff Control | 261,716 |
| Illicit Discharge Detection and Elimination (IDDE) | 37,507 |
| Industrial and Commercial Management Programs | 42,318 |
| Overall Stormwater Program Management | 281,502 |
| Pollution Prevention and Good Housekeeping for Municipal Operations | 3,510,806 |
| Post Construction Water Management in New Development and Redevelopment | 38,517 |
| Public Education, Outreach, Involvement, and Participation | 361,440 |
| Water Quality Monitoring | 494,577 |
| Watershed Management | 31,591 |
| **Total** | **5,059,973** |

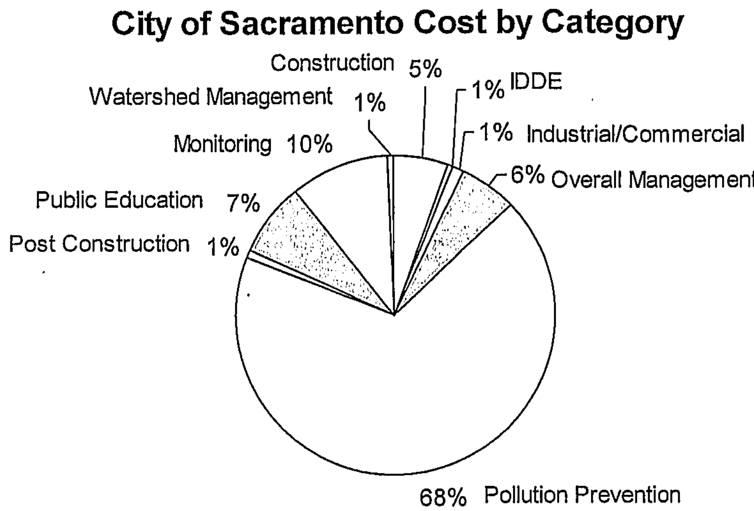


**Figure 7-1. Distribution of Sacramento Stormwater Costs Among the Cost Survey Categories**

### 7.2.1 Discussion of Costs for Each Survey Category

Cost breakdown and calculations for each survey category are found in Appendix E, Table E-1. The costs for each survey category are discussed in this section.

*Construction Site Stormwater Runoff Control*

The construction program cost was $261,716, which was 5 percent of overall stormwater cost. The construction program oversaw 417 active construction sites (Sacramento, 2003b) and performed 6,375 inspections. The average cost was $29 per inspection and $628 per active construction site.

*Illicit Discharge Detection and Elimination*

The IDDE program cost was $37,507, which was less than 1 percent of total stormwater cost. This cost is the only item attributed to this program and represents stormwater staff labor.

*Industrial and Commercial Management Programs*

The industrial and commercial management program cost was $42,318, which was less than 1 percent of total stormwater cost. The only cost attributable to this program was for the development of BMP handbooks and labor to do inspections.

*Overall Stormwater Program Management*

The overall management program cost was $281,501, which was 6 percent of total stormwater cost. Costs in this program were for office products, annual reporting, planning, mailing, CASQA fees, NPDES fee, and legal fees.

*Pollution Prevention and Good Housekeeping for Municipal Operations*

The municipal operations program cost was $3,510,806, which was 69 percent of total stormwater cost. The two primary activities for this category were street sweeping and pump station cleaning. The average cost was $50 per curb mile swept. Street sweeping and pump station costs are about 38 percent and 12 percent of total stormwater cost respectively. These percentages are based on the estimates provided by city staff and do not include labor cost allocated to oversee this program. Street sweeping costs were discounted because the city performed additional sweeping in their downtown area that was not permit required. This may be an unfair comparison to other permits that are vaguer about the sweeping requirements. In these programs (see Fresno-Clovis Metropolitan Area as an example), all sweeping costs were included because it was assumed that all sweeping was in compliance with the permit. The discounted amount for Sacramento's street sweeping costs was $277,252.

*Post Construction Stormwater Management in New Development and Redevelopment*

The post construction program cost was $38,517, which was less than 1 percent of total stormwater cost. Post construction cost was primarily for stormwater staff labor and student intern labor associated with working with developers to assure deployment of appropriate post construction BMPs. In addition, $2,500 was spent for the development of BMP handbooks.

*Public Education, Outreach, Involvement, and Participation*

The public education and outreach program cost was $361,440, which was 7 percent of total stormwater cost. The largest cost for this program was labor, which included both stormwater staff and student internship labor. The total labor cost was approximately 45 percent of the total public education and outreach program cost. The cost of development of integrated pest management (IPM) was about 11 percent and television and newspaper advertisements constituted 19 percent and 5 percent, respectively.

*Water Quality Monitoring*

The monitoring program cost was $494,577, which was 10 percent of total stormwater cost. Modeling and data analysis accounted for $131,688. Sample collection and lab cost accounted for $303,077. Stormwater staff and student labor accounted for $59,812.

*Watershed Management*

The cost of this category was $31,591, which was less than 1 percent of total stormwater cost. The primary cost attributed to this category was for stormwater staff labor.

## 7.3 CONFIDENCE IN THE DATA

For the city of Sacramento, confidence in the data was moderate. Several factors were considered in this assessment. The costs for street sweeping and pump station cleaning were estimated and represent approximately 34 percent of total stormwater program cost for the city. Since 34 percent of total stormwater cost was based on estimates, a higher level of confidence in the data could not be allowed. Secondly, the labor and direct cost data was submitted in spreadsheets built, maintained, and updated by the city staff with the labor costs being based on accounting system generated cost figures. The confidence in the data for Sacramento would be noticeably increased if 2003/04 data were considered (Busath, personal communication, 11/23/04). The city of Sacramento had a fund (Storm Drainage) set up to account for overall stormwater expenditures. Total expenditures for the Storm Drainage fund were $30,926,000[6] (City of Sacramento, 2003a), while total stormwater costs submitted by city staff were $5,046,157. This difference is attributed to the expense for flood control and conveyance work not required by the NPDES permit. Differentiation of stormwater costs in the CAFR was not possible.

[6] This figure represents the sum of operating expenses, interest expense, amortization of deferred charges, loss on disposition of fixed assets, and transfers out.

The city of Santa Clarita is a small to medium-sized city with a population of 151,088 (www.census.gov). The city lies approximately 25 miles from the Pacific coastline in the Santa Clara River watershed. The stormwater program is coordinated by the Field Services Department. Descriptive characteristics for the city of Santa Clarita are shown in Table 8-1. Primary personal communication was with Oliver Cramer and Travis Lange from the city of Santa Clarita. The city of Santa Clarita costs for 2002/2003 were for complying with their 2001 stormwater permit (RWQCB, Los Angeles, 2001).

**Table 8-1. Select Characteristics of the City of Santa Clarita**

| Description | Characteristic | Reference |
|---|---|---|
| Mean Income Per Person, $ | 26,841 | www.census.gov |
| Area, (sq. miles) | 48 | www.census.gov |
| Population | 151,088 | www.census.gov |
| Curb Miles Swept | 46,800 | Cramer, pers. comm., 4/22/04 |
| Active Construction Sites | 64 | Santa Clarita, 2003b |
| Industrial and Commercial Sites | 1,071 | Santa Clarita, 2003b |
| Households | 52,442 | www.census.gov |
| City Actual General Fund Revenue, $ | 61,659,874 | Santa Clarita, 2003a |
| Annual Rainfall (cm)[1] | 33 | www.wrcc.dri.edu |
| Years Since Incorporation | 17 | www.santa-clarita.com |

1. Dry Canyon Reservoir rain gage was used.

## 8.1 DATA SOURCES

The following describes the information available from the data sources.

*Los Angeles County Municipal Storm Water Permit (Order 01-182) Individual Annual Report Form, Attachment U-4*

This report was the primary source of cost data for the city of Santa Clarita. The report contained labor and direct cost information for the city's stormwater program broken down into categories (Appendix F, Table F-1). The labor cost is described as "Administrative Costs" and were assigned to the Overall Stormwater Management category because the city was unable to distribute these costs among the programs. This report also provided activity statistics (e.g. curb miles swept) for various city stormwater programs. These statistics were used to normalize costs to allow comparison with other cities.

*Personal Communication: Interviews, Phone Calls, E-Mail*

Through personal communication, city staff elaborated on what was accomplished for each cost submitted in their spreadsheet and commented on the allocation of costs among the cost survey categories.



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*Comprehensive Annual Financial Report (CAFR) 2002/03*

During the 2002/03 fiscal year, the city of Santa Clarita had a fund in place to account for overall stormwater related transactions. This fund is called the "Stormwater Utility" fund (Santa Clarita, 2003a). The cost figures in this fund were used for comparison purposes with costs submitted by city stormwater staff.

## 8.2 COST DATA SUMMARY

Table 8-2 summarized the stormwater program costs for each cost category. Figure 8-1 shows the relative distribution of costs among the categories. Since the city staff was unable to distribute stormwater staff labor cost among the programs, it has been captured under Overall Stormwater Program Management.

**Table 8-2. City of Santa Clarita Cost Assigned to Cost Survey Categories**

| Cost Survey Category | Costs ($) |
|---|---|
| Construction Site Stormwater Runoff Control | 74,995 |
| Illicit Discharge Detection and Elimination (IDDE) | 114,831 |
| Industrial and Commercial Management Programs | 12,600 |
| Overall Stormwater Program Management | 515,352 |
| Pollution Prevention and Good Housekeeping for Municipal Operations | 859,754 |
| Post Construction Water Management in New Development and Redevelopment | 106,925 |
| Public Education, Outreach, Involvement, and Participation | 49,130 |
| Water Quality Monitoring | 3,300 |
| Watershed Management | 332,949 |
| **Total** | **2,069,836** |

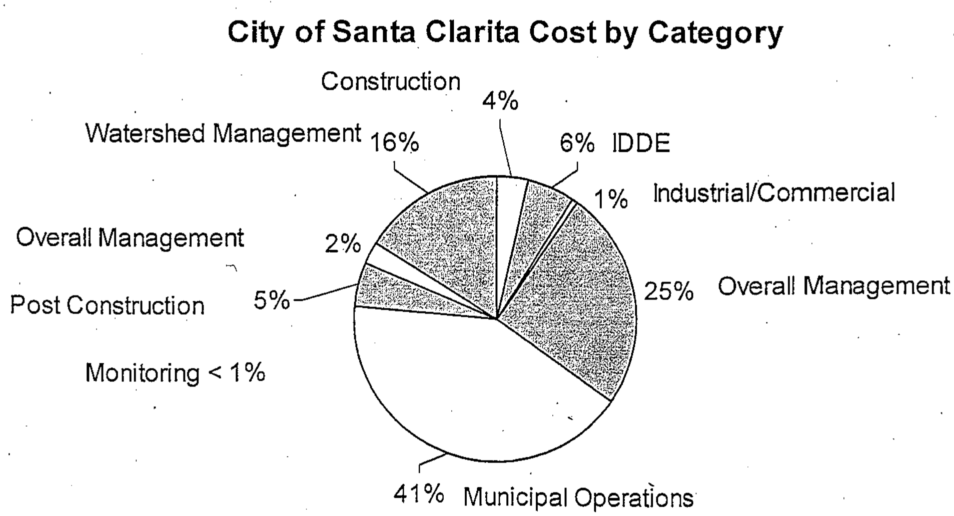




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**Figure 8-1. Distribution of Santa Clarita Stormwater Costs Among the Cost Survey Categories.**

### 8.2.1 Discussion of.Costs for Each Survey Category

Cost breakdown and calculations for each survey category are found in Appendix F, Table F-1. The costs for each survey category are discussed in this section.

*Construction Site Stormwater Runoff Control*

The construction program cost was $74,995, which was 4 percent of total stormwater cost. The construction program oversaw 64 active construction sites (City of Santa Clarita, 2003b). The average cost was $1,172 per active construction site. The city performed 11,746 inspections, but this reflects all inspections whether or not stormwater inspections were performed. Therefore, it is not appropriate to normalize against number of inspections or compare the number of inspections with other cities. (City of Santa Clarita, 2003b)

The cost of $74,995 was based on the assumption that all construction site inspections averaged a percentage of time for stormwater inspections. This was applied to the cost of all 11,746 inspections whether or not stormwater issues were addressed in all 11,746, but since an average was applied it was not necessary to eliminate non-stormwater inspections for cost estimation. The cost of $74,995 is the best estimate available for the unknown number of stormwater inspections performed in 2002/03.

The city provided an estimate of what the minimum effort might cost should stormwater inspections be performed exclusively and not more often than what is required in the permit (Cramer, personal communication, 6/24/04). Based on 64 sites, $99.21/hr for an inspector and vehicle, and 2 hrs per site including travel, the minimum cost for all inspections was calculated to be $12,699. This cost is not presented in the report, it is only presented to indicate that some cities that perform stormwater inspections concurrently with other inspections are exceeding the minimum requirements of the permit.

*Illicit Discharge Detection and Elimination*

The IDDE program cost was $114,831, which was 6 percent of total stormwater cost. The cost for this program was attributable to investigations. The average cost per investigation was $311.

*Industrial and Commercial Management Programs*

The industrial program cost was $12,600, which was less than 1 percent of total stormwater cost. The industrial program had 110 inspections at an average cost of $115 per inspection.

*Overall Stormwater Program Management*

The overall management program cost was $515,352, which was 25 percent of total stormwater cost. All of the stormwater staff cost was assigned to this category. The staff costs (including overhead allocation) represent approximately 85 percent of the costs assigned to this category and 21 percent of total stormwater cost. The other cost was $76,520 for development planning.

*Pollution Prevention and Good Housekeeping for Municipal Operations*

The municipal operations program cost was $859,754, which was 42 percent of total stormwater cost. The two primary activities for this category were street sweeping and catch basin cleaning. The average cost was $12 per curb mile swept and $170 per basin cleaning. Street sweeping cost and catch basin cleaning cost are approximately 27 percent and 12 percent of total stormwater cost respectively.

*Post Construction Stormwater Management in New Development and Redevelopment*

The post construction program cost was $106,925, which was 5 percent of total stormwater cost. Post construction cost was primarily for capital costs, which included purchase of vehicles for catch basin cleaning and ICID equipment (Cramer, personal communication, 6/24/04).

*Public Education, Outreach, Involvement, and Participation*

The public education program cost was $49,130, which was 2 percent of total stormwater cost. Public education and outreach activities often incorporated public involvement and participation activities. This made differentiating cost between the categories impractical. Because of this, the two programs were combined.

*Water Quality Monitoring*

The monitoring program cost was $3,300, which was less than 1 percent of total stormwater cost. The total cost of monitoring was $3,300, which was for monitoring for diazinon at a single location (Cramer, personal communication, 6/24/04).

*Watershed Management*

The watershed management program cost was $332,949, which was 16 percent of total stormwater cost. This cost was for the stormwater share of GIS costs.

## 8.3 CONFIDENCE IN THE DATA

For the city of Santa Clarita, confidence in the data was high. The cost data was found in the annual reporting forms. Through personal communication (Cramer, personal communication, 4/22/04) with city staff, a couple of adjustments to these numbers were made. These figures were later verified by accounting system reports and comparisons to the CAFR.

Since the city of Santa Clarita had a fund (Stormwater Utility) set up to account for overall stormwater expenditures, the level of confidence in the data was increased. This was because a comparison could be made between CAFR cost figures and those submitted by city staff. Total expenditures for the Stormwater Utility fund were $2,869,025, while total stormwater costs submitted by city staff in the annual reporting forms were $2,219,860. Non-stormwater compliance activities totaled $649,205, which exactly accounts for the difference. Because of this match with CAFR expenditures, the level of confidence in the data was increased.

Analysis of the cost survey results and comparisons to costs published independent of this survey are presented in this section. Backup calculations for the analysis presented in this section are in Appendix G. Costs are analyzed by aggregating costs for all cities and by comparing costs between individual cities.

Aggregate cost is the sum of all costs for all cities in this survey. Aggregating costs results in one cost number for total stormwater costs for all programs surveyed. This number is normalized by the number of households for all cities to calculate an average cost per household. Aggregate costs are broken down into each cost category in Section 9.2. Aggregate costs are presented by cost category and by whether they were enhanced, new, or existed prior to the first stormwater permit.

To take into account the size of the city when making comparisons, costs are normalized by number of households. Number of households was used to normalize costs in other studies. Households were selected because it is the most common cost factor from other studies. Quantitative analysis of cost factors that may affect cost per household are presented in Appendix G.

Section 9.4 presents a breakdown of both aggregate costs and individual city costs into the cost classifications of new, existing, and enhanced.

## 9.1 COST PER HOUSEHOLD

Table 9-1 presents the number of households for the cities surveyed.

**Table 9-1. Number of Households for Surveyed Areas**

| Area | Households |
|---|---|
| City of Corona | 39,271 |
| City of Encinitas | 23,843 |
| City of Fremont | 69,452 |
| Fresno-Clovis Metropolitan Area[1] | 195,311 |
| City of Sacramento | 163,957 |
| City of Santa Clarita | 52,442 |

1. The sum of the number of households for city of Clovis, city of Fresno, and the portion of Fresno County served by the FMFCD, which was calculated using the population of Fresno County served by the district, 65,000 (Pomaville, e-mail communication, 9/13/04), and average persons per household for the county (www.census.gov).

Normalized costs are presented in Table 9-2. Annual total cost per household ranged from $18 to $46 for the six cities. The small data set limits the statistical conclusions which may be drawn. Some anecdotal observations are presented below. These costs, ordered by the size of the city, are displayed in Figure 9-1.

The "true" mean in Table 9-2 is based on the sample of all households in the surveyed municipalities. It is calculated by dividing the total stormwater costs of all cities by the number of households of all cities in this survey. This gives a true average cost per household, while averaging the six cost per household values assigns equal weight to each city regardless of how many households are in each city.

**Table 9-2. Summary of Normalized Stormwater Costs for Municipalities**

| Municipalities | Municipality Description | Cost/Household ($) |
|---|---|---|
| City of Encinitas | Coastal tourism, small city | 46 |
| City of Fremont | Bay Area, moderately integrated countywide program | 45 |
| City of Santa Clarita | Tourism and industrial | 39 |
| City of Corona | Industrial | 32 |
| City of Sacramento | Pumped stormwater, large city | 29 |
| Fresno-Clovis Metropolitan Area | 65-90% infiltration, fully integrated multi-city program | 18 |
| **Summary Statistics** | | |
| Mean of the six values for each city | | 35 |
| Median of the six values for each city | | 36 |
| Standard Deviation of the six values for each city | | 11 |
| True Mean[1] | | 29 |

1. The "true" mean is the aggregate stormwater cost for all cities surveyed divided by the aggregate number of households

### 9.1.1 Going Beyond Minimum Requirements

In some cases, programs in the California survey appeared to go beyond the minimum requirements of the permit. The cost of this additional effort was not included when it could be identified or estimated, such as street sweeping in Sacramento that was above the permit required frequency. Including the total cost of the street sweeping program the cost per household for Sacramento would increase $1.69. In some cases the additional effort could not be estimated. This was particularly true when stormwater activities were combined with activities that occurred more frequently than the permit requirement for the stormwater activities, such as when stormwater construction inspections for Santa Clarita were performed at every construction permit inspection and these permit inspections occurred more frequently than the permit requirement.

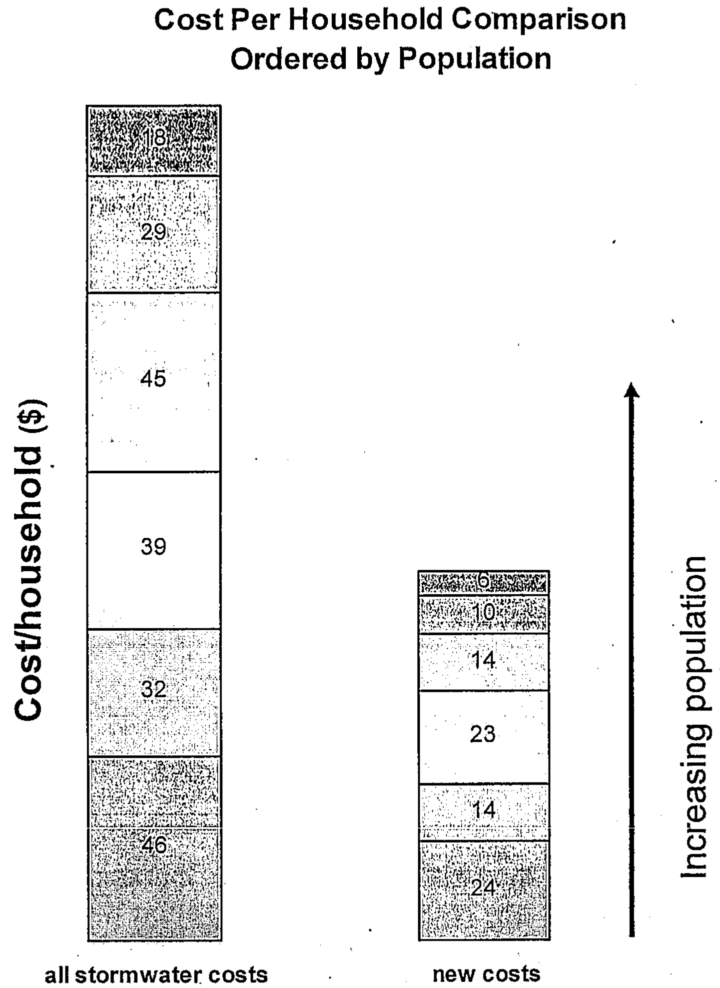



**Figure 9-1. Cost per Household Comparison of Each Surveyed City.**

### 9.1.2 Qualitative Discussion of Costs per Households

Qualitative discussion is provided here because quantitatively explaining the variation of costs per households was not successful (see Appendix G for quantitative analyses).

The FCMA had the lowest cost per household. The actual range of costs may be a smaller than what is reported in Table 9-2 because FCMA is at the bottom of this range and FCMA may not have accounted for all cost as well as other survey participants. Recall that the costs for the cities of Fresno and Clovis were based on budgeted numbers. Though the FCMA cost data collected is within the quality expectations of the study team, accounting of actual expenditures may have increased the cost for the FCMA, and decreased the range of costs found in this survey. However, even if such increases were found, FCMA costs per household would remain substantially lower than the other cities. The following factors are thought to contribute to the FCMA costs limit costs being lower than the other survey results:

- flood control and stormwater quality basins are combined,
- land was set aside for water projects,
- climate helps infiltration due to infrequent storms and low annual rainfall,
- lower land cost compared to other cities,
- FMFCD owned land needed for basins prior to storm water permits requirements,
- topography lends to drainage of urban areas to post-construction BMPs, and
- highly permeable soils allow extensive use of infiltration.

These factors are unique or more prevalent for FCMA than for the other cities surveyed. Excluding the FCMA as an ideal situation, the range of cost is tighter, $29 to $46 per household.

As see in Table 9-2, variation in cost from the other cities is not obviously explainable by the factors of size, location, tourism, and integrated co-permittee programs. These factors are discussed in the following:

**Size:** Size does not seem to be important as the large cities of Fremont and Sacramento occupy opposite sides of the cost range. Further, Encinitas, population 58,014, and Fremont, population 203,413, had almost identical cost per household. The affect of size on cost per household is shown in Figure 9-1.

**Location:** Northern versus southern parts of the state do not seem important; however, though it may be coincidental with such a small sample size, the highest cost per household, Encinitas, was adjacent to coastal waters and the next highest, Fremont, is adjacent to South San Francisco Bay.

**Tourism:** A high dependence on tourism may increase visibility of stormwater problems, such as beach closures and litter. This may not be a very important cost factor because Fremont and Encinitas have very similar cost per household, and yet Encinitas seems to have a far greater reliance on tourism.

**Integrated programs:** An integrated program is one in which an overseeing agency establishes a common approach in implementing stormwater activities. Certainly in the case of FCMA, an integrated program seems to be an important factor. No other city surveyed had a program in which a single agency implemented a comprehensive plan for post-construction stormwater control for all permittees as did FMFCD for the FCMA. This integration may contribute to relatively low cost per household; however, on the other extreme of the cost range was Fremont, who participates in the Alameda County Clean Water Program.

Not all qualitative factors could be discussed here. Cyre (1983) reports on other qualitative factors that often affect how much a city spends on stormwater activities. Besides the factors discussed above, perceived equity, public acceptance (i.e. willingness-to-pay), and jurisdictional considerations are expected to have an influence on costs.

## 9.2 AGGREGATE COST BREAKDOWN BY COST CATEGORIES

The distribution of total stormwater costs among the cost categories is shown in Figure 9-2. Note that pollution prevention costs are subdivided into the percent of cost attributed to street sweeping and the percent for all other pollution prevention activities.

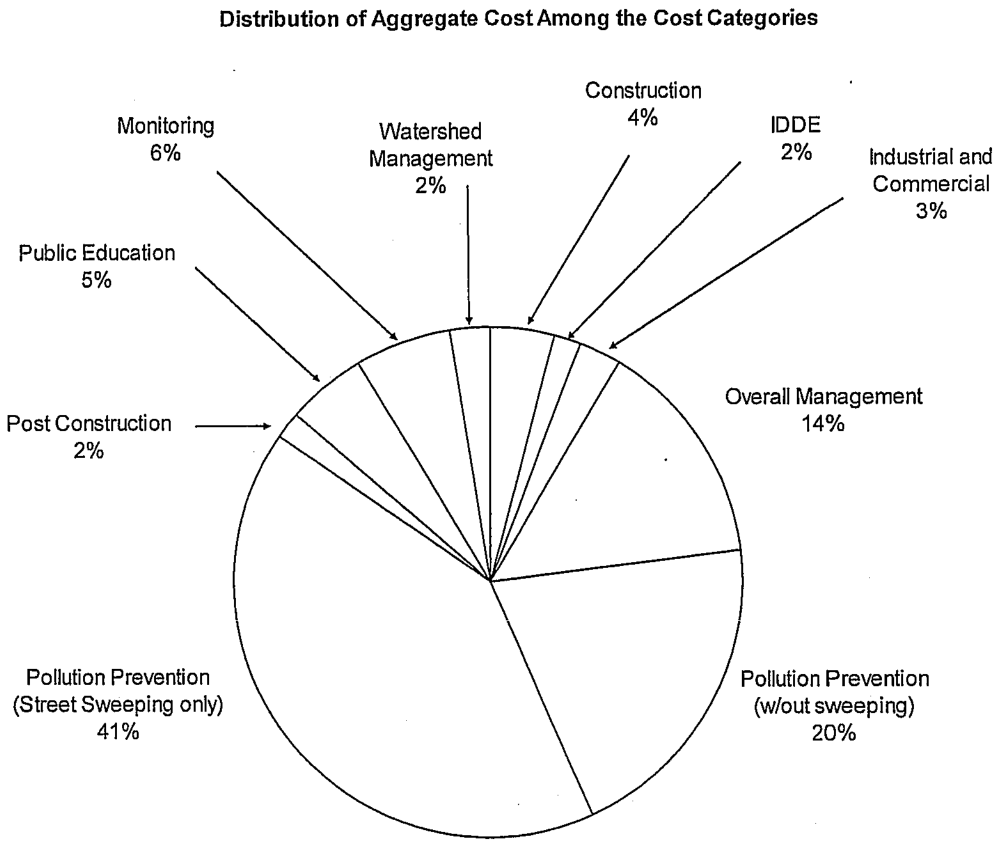



**Figure 9-2. Distribution of Aggregate Costs among Cost Categories**

## 9.3 NEW, EXISTING, AND ENHANCED COSTS

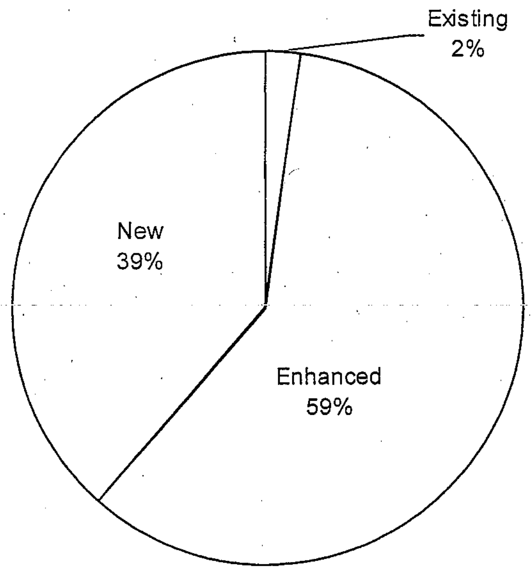
Costs for all stormwater activities were identified as new, existing, or enhanced according to the extent that the activity existed before the first stormwater permit. New costs are for activities that are exclusively a result of compliance efforts with the stormwater permit.

**Understanding Enhanced Costs**

Some stormwater activities preexisted stormwater permits, but permit requirements caused an increase in effort. Enhanced costs include all costs of these impacted activities, and not just the additional amount due to the increase in activities.

Existing costs are for activities that predated stormwater permits. Enhanced costs are for existing activities that were increased due to permit requirements. Street sweeping is a common example of an enhanced activity. Enhanced costs really consist of an unknown fraction of existing and new costs. In the street sweeping case, it seems that the majority, if not all street sweeping costs for some cities, preexisted stormwater permits. Other cases may be similar. Enhanced costs include street sweeping, drain and channel cleaning, and pump station cleaning. Enhanced costs are the total costs for the impacted activities, and not just the increase in cost. Table 9-3 shows the percentage of stormwater costs attributed to new, existing, and enhanced for each city. The distribution of aggregate cost among these classifications is shown in Figure 9-3.

Distribution of Aggregate Cost Between New, Enhanced, and Existing Costs




New, Enhanced, and Existing are determined by whether the cost existed prior to the first stormwater permit. Enhanced cost existed, but permit requirements caused an increase in cost. Enhanced costs are the total cost for the impacted activities, and not just the increase in cost.

**Figure 9-3. Breakdown of Aggregate Costs into New, Existing, and Enhanced Costs**

It was proposed in meetings of the TAG that cities with utility fees for stormwater may be less likely to have a high percentage of enhanced costs. This was not observed in the cities surveyed. In fact, cities with a stormwater fee happen to have a larger percentage of 'enhanced' costs, but the observation is not conclusive due to limited sample size. This observation is shown in Table 9-3.

**Table 9-3. New, Existing, and Enhanced Cost for Each City**

| Municipality or Area | Existing | % Ex. | Enhanced | % En. | New | % New | Total | Utility Fee |
|---|---|---|---|---|---|---|---|---|
| City of Corona | 37,651 | 3% | 651,850 | 52% | 561,365 | 45% | 1,250,866 | no |
| City of Encinitas | 16,250 | 1% | 490,786 | 45% | 580,002 | 53% | 1,087,038 | no |
| City of Fremont | 200,000 | 6% | 1,915,836 | 62% | 985,605 | 32% | 3,101,442 | yes |
| Fresno-Clovis Area | 57,539 | 2% | 2,211,196 | 63% | 1,206,295 | 35% | 3,475,029 | yes |
| City of Sacramento | 0 | 0% | 3,257,674 | 68% | 1,562,299 | 32% | 4,819,973 | yes |
| City of Santa Clarita | 50,403 | 2% | 809,351 | 39% | 1,210,082 | 59% | 2,069,836 | yes |
| **Total** | **361,842** | | **9,336,694** | | **6,105,648** | | **15,804,184** | |

All the enhanced cost activities are under the Pollution Prevention cost category. Of the 59 percent of aggregate cost attributable to enhanced costs, 70 percent was for street sweeping. Figure 9-4 shows the distribution of enhanced cost among the pollution prevention activities.

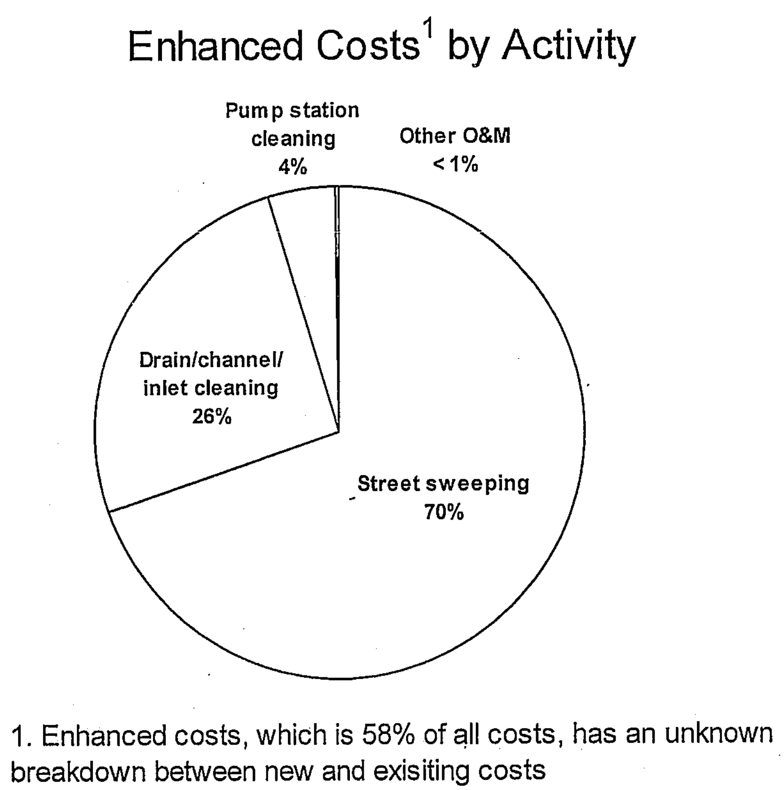



**Figure 9-4. Breakdown of Enhanced Costs by Stormwater Activity**

Existing costs, while only two percent of all cost, are mostly pollution prevention costs as seen in Figure 9-5. A single activity for one city, litter and debris removal for the city of Encinitas, accounts for 66 percent of the existing pollution prevention cost for all cities.

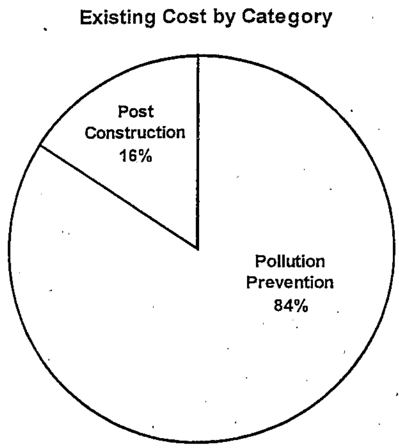



**Figure 9-5. Breakdown of Existing Costs by Cost Category**

New costs include cost from all categories. One hundred percent of all categories under "new" were identified as new cost, except for post construction and pollution prevention. Figure 9-6 shows the distribution of new costs among the cost categories.

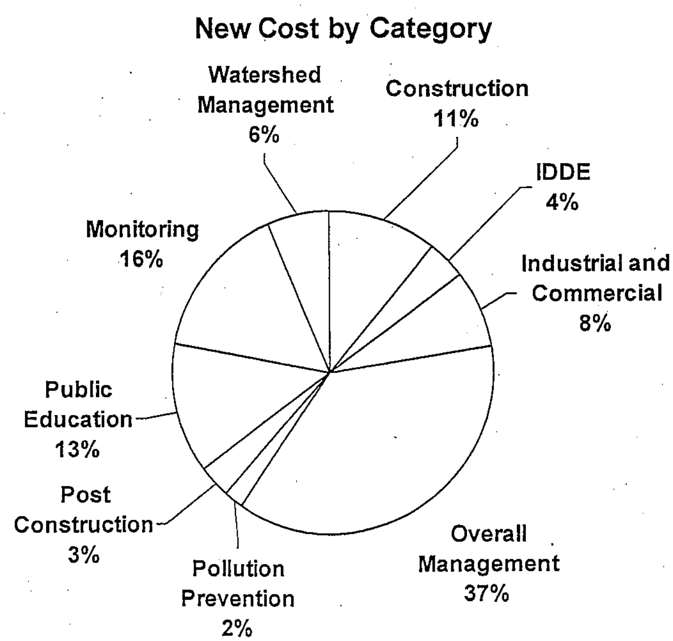



**Figure 9-6. Breakdown of New Costs by Cost Category**



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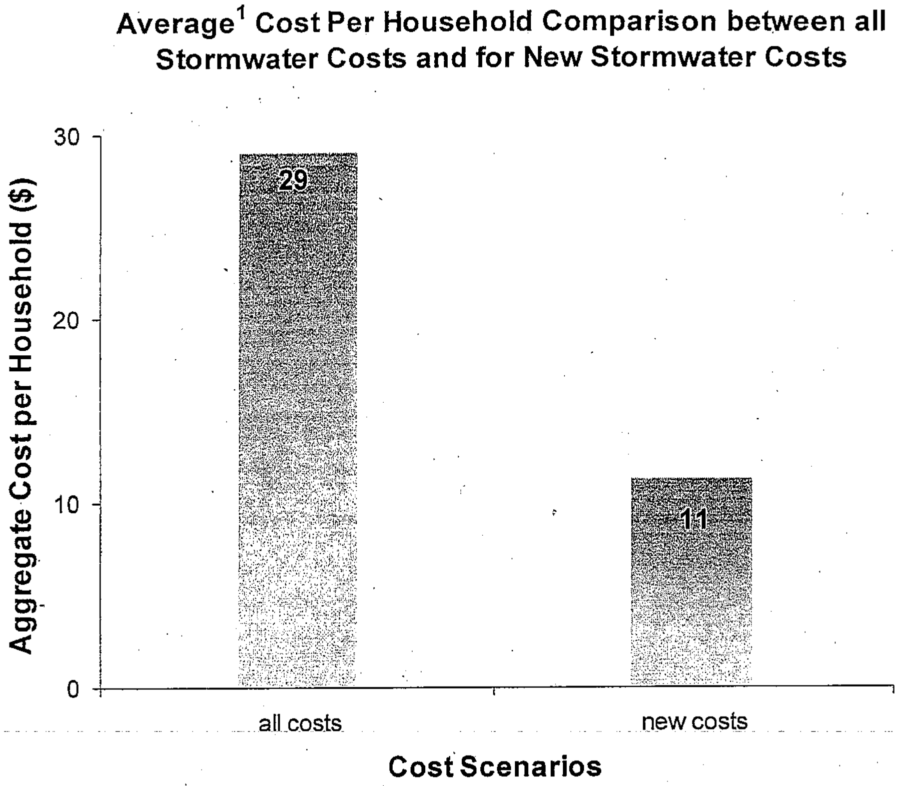
The distribution, among new, existing, and enhanced, of aggregate cost for all cost categories is shown in Table 9-4. Figure 9-7 shows average cost per household for all stormwater costs and for only new stormwater costs.

**Table 9-4. Distribution of Aggregate Cost Category between New, Existing, and Enhanced Classifications[1]**

| | % New | % Existing | % Enhanced[2] |
|---|---|---|---|
| Construction | 100% | 0% | 0% |
| IDDE | 100% | 0% | 0% |
| Industrial and Commercial | 100% | 0% | 0% |
| Overall Management | 100% | 0% | 0% |
| Pollution Prevention | 1% | 3% | 96% |
| Post Construction | 78% | 22% | 0% |
| Public Education | 100% | 0% | 0% |
| Monitoring | 100% | 0% | 0% |
| Watershed Management | 100% | 0% | 0% |

1. New, Enhanced, and Existing are determined by whether the cost existed prior to the first stormwater permit. Enhanced cost existed, but permit requirements caused an increase in cost.
2. Enhanced costs are the total cost for the impacted activities, and not just the increase in cost and as such, enhanced costs are made of unknown distribution between new and existing costs.




1. Average cost per household is the aggregate cost divided by the aggregate number of households.

**Figure 9-7. Comparison of Aggregate Cost per Household for All Costs and for New Costs**

## 9.4 DISCUSSION OF STORMWATER COSTS FOR SELECTED COST CATEGORIES

Noteworthy observations of costs for select categories are presented in this section. Only a qualitative discussion is warranted due to insufficient data.

**Overall Stormwater Management**: This category included legal fees. Appellant fees are excluded, but legal advice on program implementation and response to citizen suits are included. It is assumed that if legal fees are incurred, it is a cost of running a stormwater program. Legal costs were always less than 18 percent of the total cost of this category.

**Pollution Prevention**: Street sweeping accounts for 68 percent of the cost of this category as seen in Figure 9-8. The unit cost of street sweeping was a commonly asked question during TAG reviews. A summary of street sweeping statistics is presented in Table 9-5. No explanation was identified for the variation in street sweeping costs, though it does not exceed the estimated cost from the Rouge River study (see Section 9-6 for comparisons). One suggestion not observed in the data is that frequency has an effect on unit cost because more frequent sweeping increase cost efficiency. Table 9-5 shows unit cost of street sweeping and approximate frequency sorted by unit cost. Clearly, differences in street sweeping practices, such as sweeper speed, will affect costs.

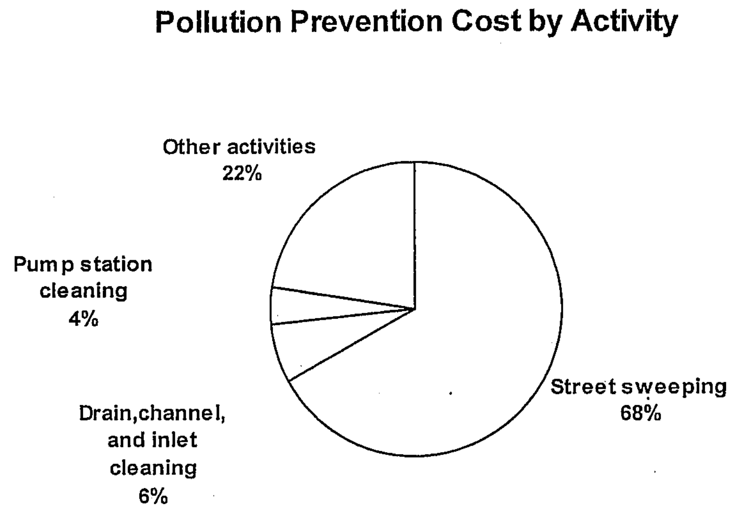



**Figure 9-8. Breakdown of Pollution Prevention Costs by Activity.**

**Table 9-5. Street Sweeping Statistics for Municipalities**

| Municipality | Street Sweeping Costs ($) | Annual Curb Miles Swept | Cost Per Curb Mile Swept ($/curb mile) | Estimated Annual Frequency[2] |
|---|---|---|---|---|
| Fremont | 1,915,000 | 31,405 | 61 | 12 |
| Sacramento | 1,322,748 | 26,450 | 50 | 12 |
| Encinitas | 117,962 | 5,832 | 20 | 12 |
| Corona | 414,215 | 20,877 | 20 | 26 |
| Fresno-Clovis Area[1] | 2,193,296 | 142,411 | 15 | 12 |
| Santa Clarita | 557,443 | 46,800 | 12 | 50 |

1. A breakdown of costs and number of miles swept for the cities of Fresno and Clovis can be found in Appendix Table D-5. Frequency for the city of Fresno was found at http://www.fresno.gov/public_utilities/sanitation/cleanup_street_clean.asp.
2. When an average frequency was not available, frequency was taken as the frequency for residential areas.

**Post Construction**: Post Construction costs are expected to increase dramatically as cities move into full implementation of SUSMP type requirements for new development and redevelopment.

The reported costs are particularly misleading for cost projection purposes since the research coincides with the start of SUSMP type requirements implementation.

## 9.5 LIMITATIONS

The information presented is anecdotal. It should not be used to establish a measure of compliance because of the lack of quantitative explanations for the observed variability in cost per household.

## 9.6 COMPARISONS TO OTHER STUDIES AND SURVEYS

The normalized costs from this cost survey were compared to outside literature (e.g. studies, professional papers, conference proceedings, etc.). Other cost sources include, the NAFSMA survey of Phase II costs, the USEPA review of cost submitted in Phase I permits, the Rouge River National Wet Weather Demonstration Project, street sweeping costs for the city of San Antonio, and projected cost (based on actual expenditures) for the city of Los Angeles. It is important to recognize that the study team did not establish the quality of this other data. However, in some cases literature data could be excluded based on the available information. For example, flow conveyance costs were not included in the California survey; but in some cases they were reported as stormwater costs in other studies, such as the Black and Veach "stormwater utility" survey (2002). This could be because stormwater cost estimates are used to develop a single fee that is used to fund both conveyance and NPDES permit compliance activities.

### 9.6.1 Current Los Angeles Cost Estimate

Staff of the Los Angeles Regional Water Quality Control Board estimated the cost to comply with the Los Angeles County municipal storm water permit. Using the estimation method believed to be most reliable, Radulescu and Swamikannu (2003) estimated cost per household to be $18. It does not appear that stormwater conveyance costs were included in these costs.

### 9.6.2 National Association of Flood and Stormwater Management Agencies (NAFSMA) Survey

The USEPA report "Economic Analysis of the Final Phase II Stormwater Rule" contains a summary of costs from two separate efforts to estimate Phase II cost per household. The first is the results of a survey stormwater costs for 56 Phase II municipalities performed by NAFSMA. The NAFSMA survey of five cost measures represents the six minimum measures of the Phase II regulations because two measures seemed to have been combined: 1) Public Education and Outreach and 2) Public Involvement and Participation.

The second effort presented in the USEPA report is that of a review, performed by USEPA, of 26 Phase I municipalities. These 26 municipalities were chosen they were relatively small Phase

I cities, they were nearly in the first permit term, and they had cost published in their annual reports.

The California survey results for the same five minimum measures were extracted to compare to the NAFSMA survey and the EPA review in Table 9-6. The costs were adjusted to 2003 dollars using the Consumer Price Index Urban (U.S. Bureau of Labor Statistics, 2005).

**Table 9-6. Stormwater Costs per Household for Six[1] Minimum Measures from the California Survey, the NAFSMA[2] Phase II Survey, and the USEPA review of Phase I Annual Reports (USEPA, 1999)**

| Study | Median (50%) ($) | Mean ($) | Max ($) |
|---|---|---|---|
| Adjusted California Survey[3] | 24 | 26 | 35 |
| NAFSMA Phase II Survey[4] | 4.63 | 10 | 61 |
| EPA Phase I Survey[5] | 3.16 | 10 | 67 |

1. Public Education and Outreach and Public Involvement and Participation were assumed combined for the NAFSMA survey.
2. NAFSMA: National Association of Flood and Stormwater Management Agencies
3. Based only on costs from cost categories that correspond to the six minimum measures
4. NAFSMA survey based on 56 Phase II respondents to a survey on stormwater costs for five minimum measures. Values adjusted to 2003 dollars.
5. EPA results based on a review of 26 annual reports for smaller Phase I cities that were nearly in their first NPDES term so that costs would be more representative of Phase II programs. Values adjusted to 2003 dollars.

### 9.6.3 Rouge River National Wet Weather Demonstration Project (Furguson, 1997)[7]

This study collected cost information for stormwater runoff controls. Total stormwater costs for municipalities in the Rouge River project were not reported. Costs were available for municipal operations and for public education. These costs are not presented here because further information is needed to indicate how the California cities compare to the Rouge River programs. First, municipal operations often include flood conveyance costs and without further information, cost comparisons are not appropriate. Second, without knowing the total stormwater cost of these cities, comparison to individual programs are not presented because cities may focus on different stormwater programs (different cost categories) based on local concerns. This may be especially true of public education costs.

Costs were also available for street sweeping. The Plymouth Township street sweeping costs were reported at $78/curb mile. This number can be compared to the range of cost per curb mile in the California survey, which was $12 to $61 per curb mile. Also, the reported cost range for contracted street sweeping costs for the Rouge River project was from $149 to $172 per curb mile. It was not investigated why contracted street sweeping is so much higher.

[7] All Rouge River costs were presented in 1997 dollars and these were converted to 2003 dollars.

### 9.6.4 San Antonio Street Sweeping Costs

The city of San Antonio is reported to spend $3.5 million on street sweeping (Brazozowski, 2004). The city of San Antonio estimates that around 45,000 curb miles were swept (Martinez, 2004). This results in a cost per mile swept of $78. The highest cost per mile from the California survey was $61, indicating costs per mile from the survey are reasonable despite a wide range.

This section discusses the significance of cost survey results and suggests standards for reporting cost and activities performed. These suggestions are meant to build the dataset necessary to make management decisions on stormwater program implementation.

## 10.1 SIGNIFICANCE OF SURVEYED STORMWATER COSTS IN CALIFORNIA

The range of 2002/03 fiscal year stormwater costs for the six municipal areas[8] surveyed was $18 to $46 per household. This only provides a snap shot of costs in 2002/2003 of good California Stormwater programs. Costs will change as requirements change with each new permit.

A specific example of increasing permit requirements is TMDL compliance. TMDL costs are sometimes addressed within the implementation plans or the cost to achieve water quality objectives may already be addressed in 305 (b) reports[9]. Since TMDL requirements will be added to stormwater permits, these cost estimates are an indication of how permit compliance costs will be increasing. However, TMDL allocations may be distributed to a variety of sources besides stormwater, thus stormwater treatment will not bear the entire burden of restoring beneficial use to impaired waters.

Another factor affecting cost in the near term is the increased level of attention given to Standard Urban Stormwater Mitigation Plans (SUSMPs). Post-construction costs in particular are expected to increase significantly, but that cost may be borne by developers and contractors rather than municipalities.

Although compliance with construction and industrial permits is discussed in stormwater permits, the costs for municipalities to comply with these permits are not addressed in this report.

## 10.2 SUGGESTIONS FOR REPORTING COSTS AND ACCOMPLISHMENTS

Current variability in the organization and content of the data submitted by the cities indicates standards for reporting costs and stormwater activities are needed to allow accurate cost comparisons to be made between stormwater activities. This cost information is crucial in making management decisions regarding which stormwater activities should be implemented.

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[8] The Fresno-Clovis Metropolitan Area includes the stormwater costs of the cities of Fresno and Clovis.

[9]Even if TMDL plans do not address cost, Section 305 (b) states "each State shall prepare and submit....a report which shall include...an estimate of the environmental impact, the economic and social costs necessary to achieve the objective of this chapter in such State, including an estimate of the costs of implementing such programs". First, assuming all 303 (d) listed waters are a subset of 305 (b) waters, it could be assumed that the CWA requires a cost analysis for TMDL implementation plans (which is interpreted as "each State shall prepare...". Otherwise it seems to be required in the State's "305(b) report". Either way, analysis of the cost to restore water quality may be an ongoing requirement.

The following recommendations for cost reporting are only the first step in the process of developing consistent cost reporting. This process includes notifying cities of reporting goals, receiving feedback and data from the cities, reviewing reported costs for quality and consistency, and providing feedback to the cities.

### 10.2.1 Current Variability

In this survey, there seemed be inconsistent reporting and tracking of stormwater activities and associated costs. This could be from differences in the reporting requirements for each permit. The reasons for these differences were not investigated; however, some possibilities are discussed. One reason may be that interest in cost may vary between RWQCB jurisdictions. Also, cost tracking systems used by the cities may not be designed to accurately track stormwater costs by activity. According to a survey conducted in 2001-2002, only 50 percent of 122 surveyed stormwater utilities said that their accounting system permitted cost tracking by operating activity (e.g. inlet cleaning) (Black and Veatch, 2002). Also, Radulescu and Swamikannu (2003) note that current governmental accounting standards do not require a distinction of stormwater costs. This was confirmed by a review of these standards by the study team.

### 10.2.2 Proposed Data Tracking and Reporting

A separate fund to account for stormwater related expenditures would provide cities with a starting point for stormwater cost collection. Cities would be able to use this fund for stormwater related expenditures needed for annual stormwater report preparation. It is important that the fund distinguish between stormwater permit compliance costs and stormwater conveyance costs. Having a fund in place also means that the costs reported in the fund would be subject to independent audit on a yearly basis, which would increase the level of confidence in reported cost figures. Stormwater costs should be further broken down into stormwater programs.

**Caution for Template Reporting Requirements**

Some of the templates used in annual reports reviewed during the survey had yes/no questions for stormwater activities that discouraged quantification of accomplishments.

For all programs, there are several costs that should be tracked for each cost category discussed below. The cost for labor of stormwater staff and benefits should be tracked for each program or allocated to each program on a reasonable basis. Direct costs (e.g. phone, field and office supplies, etc.) and depreciation costs (e.g. vehicles and equipment) should also be tracked for each program. Finally, overhead allocation for the entire stormwater program should be distributed to each cost category. Overhead allocation is often estimated by the cities as a straight percentage of labor cost and includes building fees, payroll, human resources, legal, administration, and other costs that provide ancillary support for stormwater activities.

As with costs, accomplishments should be tracked to support stormwater management decisions. The ultimate goal is to be able to compare cost benefit between stormwater programs and activities[10]. Reporting accomplishments in terms of receiving water quality benefit is ideal, but currently unrealistic.

Suggested cost categories and what activities they cover are discussed in the following sections.

*Construction Site Stormwater Runoff Control*

Stormwater permits require cities to implement construction programs that minimize the negative impacts of construction on MS4 stormwater quality. This is commonly accomplished by establishing city ordinances that give the city the legal authority to implement to program. This is a parallel and separate effort from the statewide construction permit issued by the SWRCB. The construction program assists contractors and developers in following appropriate USEPA guidelines for construction sites. Cities accomplish this by instituting ordinances, inspecting sites and providing training to contractors and city inspectors. The USEPA activities that apply to construction sites are divided into four different categories: runoff control, sediment control, erosion control, and good housekeeping. Runoff control activities include minimizing clearing, stabilizing drainage ways, and installing check dams, berms, grass-lined channels, and riprap. The sediment control category includes installing perimeter controls, installing sediment trapping devices, installing drain inlet protection. Erosion control activities include stabilizing exposed soils, permanent seeding, installing sod, soil roughening, protecting steep slopes, geotextiles, gradient terraces, soil retention, temporary slope drain, protecting waterways, temporary stream crossings, vegetated buffers, phase construction, construction sequencing, and dust control (USEPA, 2004).

Cost of stormwater inspections at construction sites, the number of inspections performed, and the number of active construction sites should be tracked. Only inspections should be tracked when stormwater issues are being addressed by a part of the inspection. It is suspected that some building inspectors still count inspections toward stormwater for latter phases of projects, such as interior building work, that has little impact on stormwater. This should be avoided.

Cost of training provided to inspectors and contractors should be tracked, including the cost for the participating inspectors to attend the training. The number of person-hours trained should be tracked for stormwater staff inspectors because the city must pay for each city staff member attending training. For contractor training, the number of training hours provided (regardless of group size) should be reported because the cities do not pay for the contractors to attend as they do for city staff.

*Illicit Discharge Detection and Elimination*

The IDDE program seeks to identify and eliminate illicit discharges to the storm sewer system. This is done by inspecting connections to the storm sewer system and requiring landowners to remediate illegal discharges. Common IDDE problems include failing septic systems,

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[10] A subcommittee of the California Stormwater Quality Association (CASQA) is working on developing guidelines for program effectiveness evaluation.

industrial/business connections, recreational sewage, and sanitary sewer overflows. Costs relating to the activities of identifying illicit connections, wastewater connections to the storm drain system, and illegal dumping should be reported in this category (USEPA, 2004).

For the IDDE program, the cost of inspections for illicit connections and discharges to the stormwater drainage system and the number of inspections should be tracked. Like construction, it is difficult to account for stormwater costs because many activities performed by inspectors serve other purposes, such as inspection of the sanitary sewer system.

Cost of training provided to inspectors should be tracked, including the cost for the participating inspectors to attend the training. The number of person-hours trained should be tracked for stormwater staff inspectors in order to effectively allocate overhead cost.

### *Industrial and Commercial Management Programs*

Similar to the construction program, the industrial and commercial program uses the development and enforcement of city ordinances to minimize pollution of MS4 stormwater. Examples of practices employed by facilities include good housekeeping such as covered material storage, emergency spill equipment, facility sweeping, no "hosing off" into storm drains, and secondary containment of industrial materials.

For the industrial and commercial program, the cost of inspections should be tracked as well as the number of industrial and commercial facilities. Also, the cost of training provided to inspectors should be tracked, including the cost for the participating inspectors to attend the training. The number of person-hours trained should be tracked for stormwater staff inspectors.

### *Overall Stormwater Program Management*

The costs in this category are for stormwater staff costs that could not be allocated to the other cost categories. It includes costs associated with development and oversight of the entire stormwater program. Also, costs for management plans, NPDES fees, reporting, mail, legal support, travel, conferences, printing, producing manuals and handbooks, and other non-labor costs are included that could not be allocated. Normalization for this category is not practical because of the wide variety of activities, and because very few of these activities can be numerically quantified.

### *Pollution Prevention and Good Housekeeping for Municipal Operations*

This program includes costs for source control activities relating to pet waste collection, automobile maintenance, vehicle washing, illegal dumping control, landscaping and lawn care, pest control, parking lot and street cleaning, roadway and bridge maintenance, septic system controls, storm drain system cleaning, and alternative discharge options for chlorinated water. Costs for materials management would be for alternative products, hazardous materials storage, road salt application and storage, spill response and prevention, used oil recycling, and materials management (USEPA, 2004).

For this program, the cost for street sweeping and the number of curb miles swept should be tracked. Also, the cost for drain line and channel cleaning, pump station cleaning, and similar activities along with their associated activity statistics (e.g. lbs. of debris removed) should be tracked. .

*Post Construction Stormwater Management in New Development and Redevelopment*

This program assures that private developers implement post-construction BMPs (treatment BMPs[11] and permanent source control BMPs). This program also includes maintenance of post-construction BMPs on city-owned property. This cost is included, because unlike the construction and industrial programs, post-construction requirements are not regulated by a separate permit.

Treatment BMPs include ponds, dry extended detention ponds, wet ponds, infiltrations practices, basins, trenches, porous pavement, filtration practices, bio-retention, sand and organic filters, vegetative practices, stormwater wetland, grassed swales and filter strips, runoff pretreatment practices, catch basins and inserts, in-line storage, and manufactured products for stormwater inlets. Source control[12] or source reduction BMPs include the following activities: experimental practices, alum injection, on-lot treatment, better site design, buffer zones, open space design, urban forestry, conservation easements, infrastructure planning, narrower residential streets, eliminating curbs and gutters, green parking, alternative turnarounds and pavers, BMP inspection and maintenance, ordinances for post construction runoff, and zoning (USEPA, 2004). If the city performs these activities in-house, the costs should be included in this category.

*Public Education, Outreach, Involvement, and Participation*

Education and outreach to homeowners would cover topics such as lawn and garden care, water conservation practices, pet waste, trash management, and proper disposal of hazardous waste. General outreach would include outreach relating to commercial activities, tailoring outreach programs to minority and disadvantaged communities and children, classroom education, and educational materials. Outreach relating to new development and existing development would include low impact development, educational displays, pamphlets, booklets, and utility stuffers, media, promotional giveaways, and pollution prevention for businesses. Relating to public involvement and participation, activities would include storm drain marking, stream cleanup and monitoring, volunteer monitoring, reforestation programs, wetland plantings, adopt-a-stream programs, watershed organization, stakeholder meetings, attitude surveys, and community hotlines (USEPA, 2004).

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[11] Treatment BMPs have been called structural BMPs, but the term 'treatment BMP' is preferred since source control BMPs often have structural components.

[12] The USEPA defines these as "nonstructural", but some source controls such as berms and material covers and many erosion controls are structural so the term source control or source reduction is used in this report.

It is unclear at this time of the utility of tracking specific costs of this program and how they may be related to water quality improvements.

*Water Quality Monitoring*

The program tracks costs related to monitoring or both stormwater and receiving water quality. These costs cover preparation of monitoring plans, sample collection, sampling equipment, laboratory analysis, data analysis, and reporting.

*Watershed Management*

This program can be used to track cost for watershed meetings, meeting with stakeholders, and development of watershed management plans. It may also be an appropriate category for coordination costs for TMDL planning.

*Conclusion on Category Recommendations*

It may prove that costs cannot be reported as suggested. Flexibility in compliance is an important aspect to cost effectiveness, however, too much flexibility in reporting requirements generates a useless dataset. At a minimum, it is suggested that annual reports throughout the state follow a standard format for cost reporting, whether the one suggested here is followed or not.

## 10.3 TAG RECOMMENDATIONS FOR COST TRACKING

The TAG proposes that if the permittees have a correct cost accounting/reporting system, they would be granted an additional quantity of points towards their receipt of a grant under a state/federal program; for example, Section 319(h) grants are evaluated on a point ranking system that is established by a state. If the cost accounting/reporting information were tabulated pursuant to the state's suggested format, that applicant would receive a bonus allotment equal to a boost in total points of approximately 15 percent. This would alert permittees to the benefit in competing for these grants as a prerequisite to establishing the appropriate cost accounting system. The proposed system would benefit from review and acceptance by the California League of Cities.

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U.S. Census Bureau. 2003. "United States Census 2000" http://www.census.gov

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ACCWP: Alameda Countywide Clean Water Program

BMP: best management practice[13]

CAFR: Comprehensive Annual Financial Report

CASQA: California Stormwater Quality Association

CFR: Code of Federal Regulations

CPR: Coalition for Practical Regulation

CSUF: California State University, Fresno

CSUS: California State University, Sacramento

CWA: Clean Water Act

DAMP: Drainage Area Master Plan

FCMA: Fresno-Clovis Metropolitan Area

FMFCD: Fresno Metropolitan Flood Control District

GIS: Geographic Information System

IDDE: Illicit Discharge Detection and Elimination

IPM: integrated pest management

JURMP: Jurisdictional Urban Runoff Management Program

LAFCD: Los Angeles Flood Control District

LARWQCB: Los Angeles Regional Water Quality Control Board

MEP: maximum extent practicable

MS4: Municipal Separate Storm Sewer System

NAFSMA: National Association of Flood and Stormwater Management Agencies

NPDES: National Pollutant Discharge Elimination System

[13] BMP, as used in this report, refers to conventional BMPs that operate without power or operators. It does not include advanced treatment.

OWP: Office of Water Programs

RWQCB: Regional Water Quality Control Board

SAR-DAMP: Santa Ana Regional Drainage Area Management Plan

SQIP: Stormwater Quality Improvement Plan

SUSMP: Standard Urban Storm Water Mitigation Plan

SWMP: Storm Water Management Plan

SWPPP: Storm Water Pollution Prevention Plan

SWRCB: State Water Resource Control Board

TAG: technical advisory group

TMDL: total maximum daily load

UCLA: University of California, Los Angeles

USC: University of Southern California

USD: Union Sanitation District

USEPA: United States Environmental Protection Agency

WERF: Water Environment Research Foundation

The backup calculations for the cost for each cost survey category in Section 3 and the sources of the cost data are presented in this appendix. Tables generally are presented by sequentially increasing levels of detail. Figure A-1 illustrates how data is shared throughout the tables.

Table A-1 contains all costs organized into the various standard cost survey categories. The subtotals for each cost category are also presented in Section 3, Table 3-2. The remaining tables (A-2 through A-12) present the detailed back-up information for the numbers in Table A-1. Table A-1 is linked to the back-up tables by the table and item numbers in the 'Source' column. Most of the cost information provided by city staff is listed in Table A-2. Item numbers corresponding to the subtotals in Table A-2 were added to the left hand column to easily show how the numbers are pulled forward to Table A-1. The right hand column in Table A-2 was added to show how costs were allocated to the cost survey categories. Table A-1 entries that were not taken directly from Table A-2 are found in Tables A-3 through A-12.

Table A-1 also provides statistics describing the level of effort for certain activities by numerically representing what or how much was accomplished. References are provided within Table A-1 for the activity statistics. Where relevant statistics are available, normalized costs are calculated in Table A-1. Normalized costs are calculated by dividing the cost of the category or activity by the activity statistic.

For the city of Corona, labor costs of the stormwater staff are not distributed among the cost survey categories. Instead, it is all captured under Overall Stormwater Program Management. Thus, comparing costs with other municipalities where such costs are distributed, Corona's Overall Stormwater Management Program costs will be higher.

Detailed descriptions of how the costs were developed are contained in the following paragraphs.

### *Construction Site Stormwater Runoff Control*

The total cost of this category was $53,382. The costs of the construction runoff control category include labor and vehicle usage expenses for inspections and meetings, vehicle usage expense for stormwater staff for follow-up visits, training stormwater staff for construction, and phone costs by stormwater staff. The labor and vehicle cost for inspections was taken directly from Table A-2. These inspections were performed by the Inspection Division of the Public Works Department (Michele Colbert, personal communication, city of Corona, 3/12/04).

The construction site inspectors also had weekly meetings that covered stormwater issues. City staff estimated that an average of 10 minutes per meeting were spent covering stormwater issues (Michele Colbert, pers. comm., 3/12/04). Table A-8 calculates the cost associated with covering stormwater issues in these meetings, assuming 50 meetings per year.

Follow-up visits for coordination and advisement were performed by the stormwater staff. As mentioned before, these labor costs are not allocated to the construction category because it was

Corona

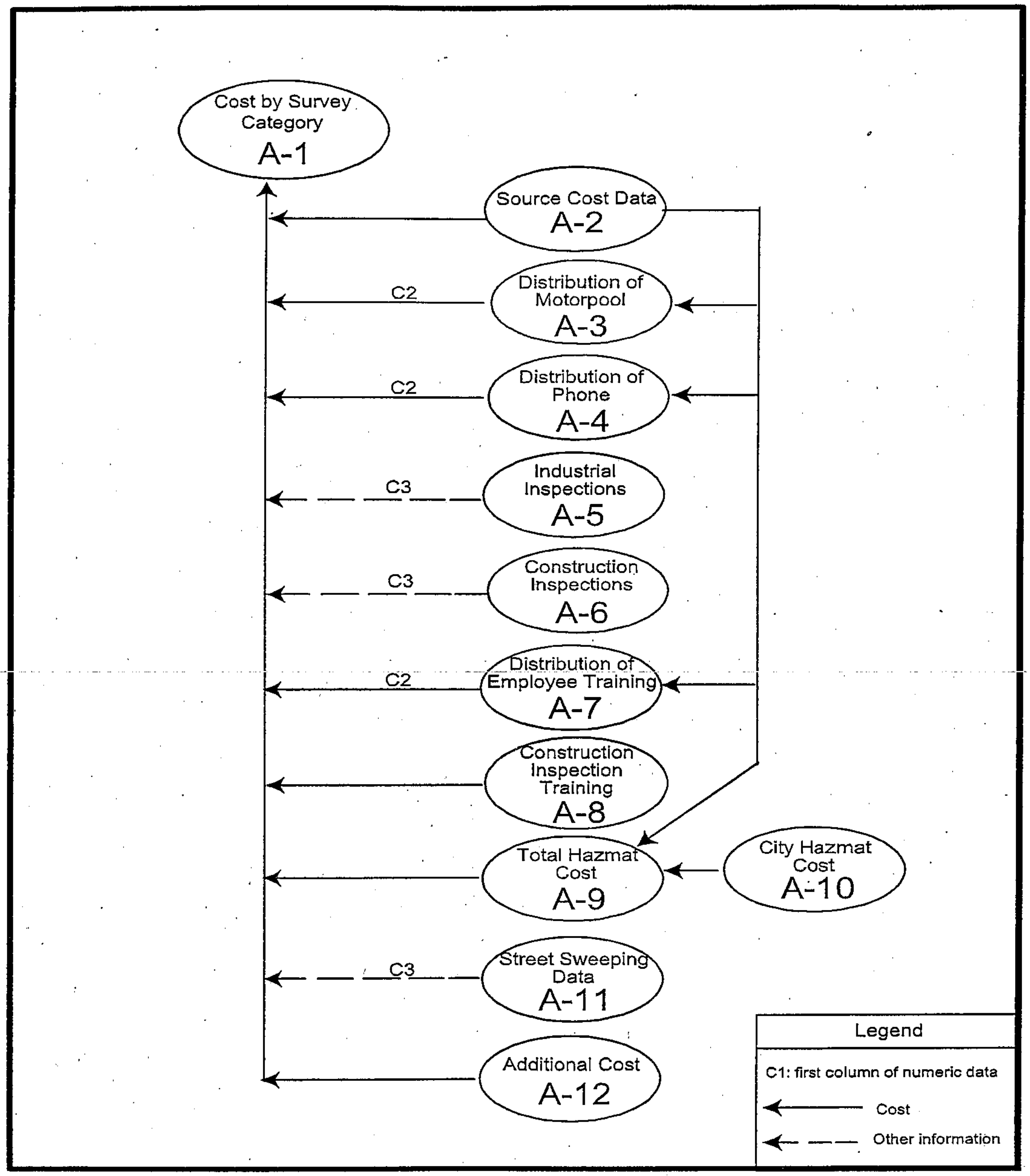


**Figure A-1. Corona Flowchart of Cost Tables**

difficult for city staff to estimate the distribution of stormwater staff time to the various categories. The allocation of vehicle usage by stormwater staff was estimated by percentages provided by city staff (Michele Colbert, pers. comm., 3/12/04). This information was used in Table A-3 in conjunction with the total cost in Table A-2 to estimate the cost of the vehicle for the construction category. Likewise, the phone charges used on these visits were allocated to construction in Table A-4.



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The city of Corona incurred employee training costs (item 26, Table A-2) that had a portion allocated to the construction category in Table A-7 according to percentages provided by city staff (Michele Colbert, pers. comm., 3/12/04).

City staff provided information regarding construction site inspections, which were summarized in Table A-6. Total inspections were calculated in Table A-6 to be 564. The overall normalized cost, calculated by dividing the total cost of the category by the number of inspections is $95/inspection.

### *Illicit Discharge Detection and Elimination (IDDE)*

The total cost of this category was $20,628. The IDDE program was implemented by the source control division and public works inspection division of the city of Corona. The costs attributed to this category were for the stormwater share of inspections performed by source control staff and inspection staff for other illicit connections at industrial, commercial, and new development sites (Table A-2). The source control inspection cost was developed by estimating how much time inspectors took looking for illicit discharges while doing regular inspections of industrial and commercial sites (3,050). Seventy such inspections were made during the 2002/03 fiscal year. The normalized cost calculated by dividing the total cost of the category by the number of inspections, is $295/inspection.

### *Industrial and Commercial Management Programs*

The total cost of this category was $89,916. This program used public works department staff to perform inspections. This cost was taken directly from Table A-2.

As in the construction category, the stormwater staff had vehicle and phone usage expenses to perform follow-up inspections and meetings for industrial facilities. These costs were based on Table A-2, items 14 and 15 and the allocations were calculated in Tables A-3 and A-4.

Training of stormwater staff for this program was allocated according to Table A-7.

### *Overall Stormwater Program Management*

The total cost of this category was $317,800. As discussed previously, stormwater staff costs were not distributed to the other categories. Stormwater staff labor costs are found in Table A-2, items 18 through 21. These costs are loaded costs that include salary, benefits, insurance, etc. Office supplies, telephone, and postage are taken directly from Table A-2, items 24 and 25. The cost of reporting was taken from Table A-2, item 34. Reporting costs paid for updating the Drainage Area Master Plan (DAMP). While not specifically required in the permit the information contained in the report is. For example, the city must address flow velocity and runoff value increases for new development (Permit, R8-2002-0011 section VIII.8-e). The information in the DAMP also allows the city to track spills and identify regional BMPs. The "administration services" charge is taken from Table A-2, item 27. This charge includes the allocation to stormwater for buildings, payroll, accounting, legal, and other overhead charges (Michele Colbert, pers. comm., 3/12/04).

### *Pollution Prevention and Good Housekeeping for Municipal Operations*

The total cost of this category was $720,222. The city of Corona contracted for street sweeping services for 2002/03. These costs are shown in Table A-2, items 1 and 2. The number of curb miles swept was provided by city staff as a stand-alone worksheet. This worksheet is reproduced in Table A-11. The personnel cost of $14,000 (Table A-2, item 2) represents labor cost for the city of Corona to oversee the street sweeping contractor. The cost per curb mile swept ($20) is calculated based on total street sweeping costs.

Drain line and channel cleaning was performed in-house. The equipment rental, labor, and vehicle rental costs are presented in Table A-2 (items 3, 4, and 5 respectively). The normalized cost for this activity is based on the sum of these three costs and the total linear feet of maintained channels and drain lines. The costs for each type of facility could not be separated. Twenty-nine percent of the total linear feet was drain pipe and 71 percent was channels (Corona, 2003a).

Corona also incurred costs for hazardous material spill response. Public works and fire departments incurred costs implementing this program. These costs are calculated in Table A-9 and are based on a stand-alone worksheet provided by city staff reproduced as Table A-10. The normalized costs for hazmat responses ($465/response) are based on the total costs divided by the total number of responses.

Cost for the maintenance of the storm drain geographic information system (GIS) was taken directly from Table A-2.

The allocation of stormwater staff training expenses related to this category are calculated in Table A-7, based on Table A-2, item 26.

The cost incurred by the fire department for implementing SWPPPs for its nine fire stations are taken directly from Table A-2, item 23.

### *Post Construction Stormwater Management in New Development and Redevelopment*

The total cost of this category was $13,509. The city staff identified two costs for this category. Both are taken directly from Table A-2. The professional services costs were for a consultant that advised the city on selection of post-construction BMPs. The drain inlet insert maintenance cost was for 8 drain inlet inserts. The normalized cost calculation gives an approximate cost per drain inlet insert of $563/insert. This normalized value is not expected to be useful in comparing program costs as part of this cost survey.

### *Public Education and Outreach* and *Public Involvement and Participation*

The total cost of these categories was $28,409. The city did not track these costs separately and dividing the costs would be an artificial exercise (Michele Colbert, pers. comm., 3/12/04). All the costs for these two categories were taken directly from Tables A-2 and A-12. The descriptions for these categories in the annual report did not contain statistics that would be useful for normalizing the costs of these categories. This was confirmed in the meetings with city staff.

### *Water Quality Monitoring*

The total cost of this category was $7,000. The cost incurred for monitoring was for ad hoc testing in support of the IDDE program. This cost can be found in Table A-2, item 31.

### *References*

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Table A-1. Corona Cost Organized by Cost Survey Category

Cost Survey Categories

*Activity Descriptions*

### Construction Site Stormwater Runoff Control

| Description | External Contract | Relation to Permit[a] | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Inspections by Public Works department* | | New | 46,184.00 | Table A-2, Item 13 | 86.5% | 564 | inspections | Table A-6 | 81.89 | $/inspection |
| *Share of stormwater issues in weekly inspector meetings* | | New | 6,013.50 | Table A-8 | 11.3% | 9 | person days | Calculation | 641.44 | $/person day |
| *Share of vehicle used by stormwater staff for construction* | | New | 419.40 | Table A-3 | 0.8% | | | | | |
| *Share of phone used by stormwater staff for construction* | | New | 28.25 | Table A-4 | 0.1% | | | | | |
| *Share of training for stormwater staff for construction* | x | New | 736.67 | Table A-7 | 1.4% | 9 | person days | Calculation | 78.58 | $/person day |
| Total | | | 53,381.82 | | 4.3% | of total stormwater cost | | | | |
| Overall Cost Category Normalizations | | | | | | | | | | |
| total category $ per inspection | | | | | | 564 | inspections | Table A-6 | 94.65 | total $/inspection |
| total category $ per active construction site | | | | | | 41 | active construction sites | Colbert, pers. comm., 3/12/04 | 1,302.00 | total $/active construction site |

### Illicit Discharge Detection and Elimination

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Stormwater share of inspections by wastewater staff* | | New | 11,007.00 | Table A-2, Item 22 | 53.4% | 70 | inspections | Colbert, pers. comm., 4/28/04 | 157.24 | $/inspection |
| *Illicit connection inspections* | | New | 9,621.00 | Table A-12 | 46.6% | 20 | inspections | Colbert, pers. comm., 4/28/04 | 481.05 | $/inspection |
| Total | | | 20,628.00 | | 1.6% | of total stormwater cost | | | 294.69 | total $/sw inspection |

### Industrial and Commercial Management Programs

| Description | External Contract | Nature | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Inspections* | | New | 80,674.00 | Table A-2, Item 11 | 89.7% | 600 | inspections | Table A-5 | 134.46 | $/inspection |
| *Share of vehicle used by stormwater staff for industrial programs* | | New | 7,968.60 | Table A-3 | 8.9% | | | | | |
| *Share of phone used by stormwater staff for industrial programs* | | New | 536.75 | Table A-4 | 0.6% | | | | | |
| *Share of training for industrial programs* | | New | 736.67 | Table A-7 | 0.8% | | | | | |
| Total | | | 89,916.02 | | 7.2% | of total stormwater cost | | | | |

### Overall Stormwater Program Management

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *100% Public Works staff* | | New | 94,476.00 | Table A-2, Item 18 | 29.7% | | | | | |
| *50% Public Works staff* | | New | 59,938.00 | Table A-2, Item 19 | 18.9% | | | | | |
| *30% Public Works staff* | | New | 34,874.00 | Table A-2, Item 20 | 11.0% | | | | | |
| *10% Public Works staff* | | New | 6,196.00 | Table A-2, Item 21 | 1.9% | | | | | |
| *Office supplies and publications* | | New | 730.00 | Table A-2, Item 24 | 0.2% | | | | | |
| *Telephone and postage* | | New | 1,200.00 | Table A-2, Item 25 | 0.4% | | | | | |
| *Administrative service charges* | | New | 79,367.00 | Table A-2, Item 27 | 25.0% | | | | | |
| *NPDES fee* | | New | 18,516.00 | Table A-2, Item 28 | 5.8% | | | | | |
| *Reporting-Drainage Master Plan* | | New | 22,503.00 | Table A-2, Item 34 | 7.1% | | | | | |
| Total | | | 317,800.00 | | 25.4% | of total stormwater cost | | | | |

## Table A-1. Continued.

### Pollution Prevention and Good Housekeeping for Municipal Operations

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| Street Sweeping | | | | | | 20,877 | curb miles swept | Table A-11 | 19.84 | $/curb mile swept |
| *Street sweeping contract* | x | Enhanced | 400,215.00 | Table A-2, Item 1 | 55.6% | | | | | |
| *Oversight of street sweeping* | | New | 14,000.00 | Table A-2, Item 2 | 1.9% | | | | | |
| *Drain lines/channel cleaning* | | | | | | 30,305 | linear feet inspected | Corona, 2003b | 8.30 | $/linear foot |
| *Equipment rental* | | Enhanced | 36,211.00 | Table A-2, Item 3 | 5.0% | | | | | |
| *Personnel* | | Enhanced | 188,856.00 | Table A-2, Item 4 | 26.2% | | | | | |
| *Vehicle rental* | | Enhanced | 26,568.00 | Table A-2, Item 5 | 3.7% | | | | | |
| *Hazmat Response* | | | | | | 41 | responses | Table A-10 | 465.15 | $/response |
| *Public Works* | | Existing | 9,621.10 | Table A-9 | 1.3% | | | | | |
| *Fire* | | Existing | 9,450.00 | Colbert, 2004 | 1.3% | 47 | responses | Colbert, pers. comm., 6/16/04 | 201.06 | $/response |
| *GIS maintenance for storm drains* | | New | 6,300.00 | Table A-2, Item 33 | 0.9% | | | | | |
| *Share of training for municipal operations* | x | New | 736.67 | Table A-7 | 0.1% | | | | | |
| *Fire department cost for SWPPP implementation* | | New | 9,685.00 | Table A-2, Item 23 | 1.3% | 9 | fire stations | Colbert, pers. comm., 4/28/04 | 1,076.11 | $/station |
| *Disposal costs for hazardous waste* | x | Existing | 12,101.68 | Table A-12 | 1.7% | | | | | |
| *Hazmat waste operator training classes* | x | Existing | 6,478.00 | Table A-12 | 0.9% | | | | | |
| Total | | | 720,222.45 | | 57.6% | of total stormwater cost | | | | |

### Post Construction Stormwater Management in New Development and Redevelopment

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Professional services (consultant)* | x | New | 9,009.00 | Table A-2, Item 29 | 66.7% | | | | | |
| *Drain inlet insert maintenance* | | New | 4,500.00 | Table A-2, Item 35 | 33.3% | 8 | inserts | Colbert, pers. comm., 3/12/04 | 562.50 | $/insert |
| Total | | | 13,509.00 | | 1.1% | of total stormwater cost | | | | |

### Public Education, Outreach, Involvement, and Participation

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Contribution to regional clean air public education program* | | New | 4,000.00 | Table A-2, Item 7 | 14.1% | | | | | |
| *Contribution to countywide public education program* | | New | 12,063.00 | Table A-2, Item 8 | 42.5% | | | | | |
| *Response to public stormwater complaints* | | New | 8,700.00 | Table A-2, Item 12 | 30.6% | | | | | |
| *Share for stormwater education in new business brochures* | | New | 300.00 | Table A-2, Item 30 | 1.1% | | | | | |
| *Household Hazardous Waste Collection Event* | | New | 3,346.00 | Table A-12 | 11.8% | | | | | |
| Total | | | 28,409.00 | | 2.3% | of total stormwater cost | | | | |

### Water Quality Monitoring

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Laboratory testing for illicit discharge program* | x | New | 7,000.00 | Table A-2, Item 31 | 100.0% | | | | | |
| Total | | | 7,000.00 | | 0.6% | of total stormwater cost | | | | |

| | | |
|---|---|---|
| Total Stormwater Costs | | 1,250,866.28 |

a. This column indicates whether required activities were being performed prior to stormwater permits. In some cases activities were enhanced due to permit requirements.

Table A -2. Primary Cost Data for Corona

| Item # | City of Corona Category | Total Cost | Cost Survey Category[1] |
|---|---|---|---|
| | ***Street Cleaning/Sweeping*** | | |
| 1 | Annual Street Sweeping Contract Cost | 400,215 | Pollution Prevention |
| 2 | Personnel Cost | 14,000 | Pollution Prevention |
| | ***Storm Drain Cleaning*** | | |
| 3 | Equipment Rental | 36,211 | Pollution Prevention |
| 4 | Personnel Cost | 188,856 | Pollution Prevention |
| 5 | Motor Pool Rental | 26,568 | Pollution Prevention |
| | ***Public Education*** | | |
| 6 | Personnel Time | 0 | |
| 7 | WRCOG - Clean Cities | 4,000 | Public Education |
| 8 | County Implementation Agreement | 12,063 | Public Education |
| | ***Hazmat Reponse*** | | |
| 9 | Cost for Fire Dept. | 5,000 | Pollution Prevention |
| | ***Plan Check Activity*** | | |
| 10 | Plan Check Activity | 0 | |
| | ***Ordinance Enforcement Activities*** | | |
| 11 | Industrial/Commercial Inspection & Follow-Up | 80,674 | Industrial |
| 12 | Residential | 8,700 | Public Education |
| 13 | Construction (Inspection Costs) | 46,184 | Construction |
| 14 | Motorpool (Explorer) | 8,388 | See Table A-3 |
| 15 | Phone | 565 | See Table A-4 |
| | ***Code Compliance*** | | |
| 16 | Code Compliance | 0 | |
| | ***Permit Administration*** | | |
| 17 | Personnel Expenses: | 0 | |
| 18 | Michele (100%) | 94,476 | Management |
| 19 | Nabil (50%) | 59,938 | Management |
| 20 | Ati (30%) | 34,874 | Management |
| 21 | Tracy (10%) | 6,196 | Management |
| 22 | Source Control (10%) | 11,007 | Illicit Discharge |
| 23 | Fire Dept. (10%) | 9,685 | Pollution Prevention |
| 24 | Office Supplies and Publications | 730 | Management |
| 25 | Telephone and Postage | 1,200 | Management |
| 26 | Employee Training and Conference | 2,210 | See Table A-7 |
| 27 | Administrative Service Charges | 79,367 | Management |
| 28 | Regional Water Quality Control Board | 18,516 | Management |
| 29 | Professional Services | 9,009 | Post Construction |
| 30 | Public Education and Information | 300 | Public Education |
| 31 | Laboratory Testing | 7,000 | Monitoring |
| 32 | Structural BMP | 0 | |
| 33 | GIS Citywide Storm Drain System | 6,300 | Pollution Prevention |
| 34 | Drainage Master Plan | 22,503 | Management |
| | ***NPDES Facilities Mitigation*** | | |
| 35 | Facilities Mitigation | 4,500 | Post Construction |
| | Total | 1,199,235 | |

(Source: Colbert, pers. comm., 3/12/04)

1. Cost Categories Abbreviated According to the Following:
   - Construction: Construction Site Stormwater Runoff Control
   - Illicit Discharge: Illicit Discharge Detection and Elimination
   - Industrial: Industrial and Commercial Management Programs
   - Management: Overall Stormwater Program Management

**Table A – 2. Continued.**

Pollution Prevention: Pollution Prevention and Good Housekeeping for Municipal Operations
Post Construction: Post Construction Water Management in New Development and Redevelopment
Public Education: Public Education, Outreach, Involvement, and Participation
Monitoring: Water Quality Monitoring
Watershed: Watershed Management

**Table A-3. Distribution of Motorpool (Explorer) between Construction and Industrial/Commercial Programs**

| Cost | Source | Percent Allocation | Category | Reference | Allocated Cost |
|---|---|---|---|---|---|
| 8,388.00 | Table 2, Item 14 | 95% | Industrial/Commercial | Colbert, pers. comm., 4/28/04 | 7,968.60 |
| 8,388.00 | Table 2, Item 14 | 5% | Construction | Colbert, pers. comm., 4/28/04 | 419.40 |
| Total | | 100% | | | 8,388.00 |

**Table A-4. Distribution of Phone between Construction and Industrial/Commercial Programs**

| Cost | Source | Percent Allocation | Category | Reference | Allocated Cost |
|---|---|---|---|---|---|
| 565.00 | Table 2, Item 15 | 95% | Industrial/Commercial | Colbert, pers. comm., 4/28/04 | 536.75 |
| 565.00 | Table 2, Item 15 | 5% | Construction | Colbert, pers. comm., 4/28/04 | 28.25 |
| Total | | 100% | | | 565.00 |

**Table A-5. Calculation of Inspections for Industrial Management Programs**

| Site Type | Source | Annual Inspections | Reference | Inspections | |
|---|---|---|---|---|---|
| High Priority | 600 | 1 | Colbert, pers. comm., 3/12/04 | 600 | |
| Medium Priority | 540 | 0.5 | Colbert, pers. comm., 3/12/04 | 0 | * |
| Low Priority | 1,910 | 0.2 | Colbert, pers. comm., 4/28/04 | 0 | * |
| Totals | 3,050 | | | 600 | |

* Inspections started in 03/04, not inspected in 02/03

**Table A-6. Calculation of Inspections for Construction Site Stormwater Runoff Control Programs**

| Site Type | Number | Annual Inspections | Reference | Inspections |
|---|---|---|---|---|
| High Priority | 6 | 24 | Colbert, pers. comm., 3/12/04 | 144 |
| Low Priority | 35 | 12 | Colbert, pers. comm., 3/12/04 | 420 |
| Totals | 41 | | | 564 |

**Table A-7. Distribution of Employee Training Among**

| Cost | Source | Percent Allocation | Category | Allocated Cost |
|---|---|---|---|---|
| 2,210.00 | Table 2, Item 26 | 33% | Construction | 736.67 |
| 2,210.00 | Table 2, Item 26 | 33% | Industrial/Commercial | 736.67 |
| 2,210.00 | Table 2, Item 26 | 33% | Municipal | 736.67 |
| Total | | 100% | | 2,210.00 |

(Source: Colbert, pers. comm., 3/12/04)

**Table A-8. Cost of Fraction of Construction Inspectors Weekly Meetings Dedicated to Stormwater Issues**

| Description | Dollar Amount or Statistic | Reference |
|---|---|---|
| Meetings per year | 50 | Corona, 2003b |
| Minutes per meeting for stormwater issues | 10 | Colbert, pers. comm., 3/12/04 |
| Number of person hours | 9 | Calculation |
| Overhead Rate | $ 80.18 | Colbert, pers. comm., 3/12/04 |
| Labor Cost | $ 6,013.50 | Calculation |

**Table A-9. Calculation of Hazmat Response Cost for Municipal Operations Program**



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| Cost Type | Amount | Source |
|---|---|---|
| Fire Department | 5,000.00 | Table A-2, Item 9 |
| Equipment | 1,040.88 | Table A-10 |
| Materials | 171.42 | Table A-10 |
| Labor | 3,408.80 | Table A-10 |
| Total | 9,621.10 | |

**Table A-10. Hazardous Materials Worksheet Submitted by City of Corona Staff**

| Actvity PHAZM | Haz Mat Cleaned Up |
|---|---|
| Number of jobs | 41 |
| Labor Hours | 129.75 |
| Labor Cost | 3,408.80 |
| Equipment Hours | 69.82 |
| Equipment Cost | 1,040.88 |
| Materials Cost | 171.42 |
| **Total Cost** | **4,621.10** |
| Average Cost/Job | 112.71 |
| Average Labor Hours/Job | 3.16 |
| Average Equipment Hours/Job | 1.70 |

(Source: Colbert, pers. comm., 3/12/04)

**Table A-11. Street Sweeping Analysis Submitted by City of Corona Staff**

| Service Type | Curb Miles | Services/Year | Annual Miles | Percentage | |
|---|---|---|---|---|---|
| Residential | 655 | 26 | 17,019 | 82% | 84% |
| Alleys (Residential) | 38 | 12 | 450 | 2% | |
| Commercial | 54 | 52 | 2,786 | 13% | 16% |
| Medians/Inter (Commercial) | 52 | 12 | 622 | 3% | |
| Totals | 797 | | 20,877 | 100% | 100% |

(Source: Colbert, pers. comm., 3/12/04)

**Table A-12. Additional Costs Identified and Submitted by the City of Corona Staff**

| Activity Description | Cost | Stormwater Program |
|---|---|---|
| Planning and labor for Household Hazardous Waste Collection Event | 3,346.00 | Public Education |
| Disposal costs for hazardous waste | 12,101.68 | Pollution Prevention |
| Hazmat waste operator training classes | 6,478.00 | Pollution Prevention |
| Illicit connection inspections | 9,621.00 | Ilicit Discharge |
| Total | 31,546.68 | |

(Source: Colbert, pers. comm., 5/18/04)

The backup calculations for the cost for each cost survey category in Section 4 and the sources of the cost data are presented in this appendix. Tables are generally presented by sequentially increasing levels of detail. Figure B-1 illustrates how data is shared throughout the tables.

Table B-1 contains all costs organized into the various standard cost survey categories. The subtotals for each cost category are also presented in Section 4, Table 4-2. The remaining tables (B-2 through B-6) present the detailed back-up information for the numbers in Table B-1. Table B-1 is linked to the back-up tables by the table and item numbers in the 'Source' column. Most of the cost information provided by city staff is listed in Table B-2. Item numbers corresponding to the subtotals in Table B-2 were added to the left hand column to easily show how the numbers are pulled forward to Table B-1. The right hand column in Table B-2 was added to show how costs were allocated to the cost survey categories. Table B-1 entries that were not taken directly from Table B-2 are found in Tables B-3 through B-6.

For the city of Encinitas, labor, supplies, travel, equipment, and vehicle costs are distributed among the various survey categories according to estimates provided by city staff (Table B-3). Thus, comparing costs with other municipalities where such costs are not distributed, Encinitas's Overall Stormwater Management Program costs will be lower.

City staff has projected new capital projects and labor that will immediately increase their costs over the next few years. Additional labor costs will relate to engineering inspections, planning, and plan checking. Capital project costs will include installation of filter inserts, fire station wash facilities, and a storm drain. Additional operation and maintenance costs will be incurred relating to these capital projects as well.

Detailed descriptions of how the costs were developed are contained in the following paragraphs.

### *Construction Site Stormwater Runoff Control*

The total cost of this category was $169,751. The city of Encinitas Building Department staff performed all 401 inspections during the wet season spanning from October 1, 2002 to April 30, 2003 (Encinitas, 2003b). The normalized cost, calculated by dividing the total cost of the category by the number of inspections, is $423/inspection. The stormwater staff also conducted the following activities in the construction category (descriptions obtained from annual stormwater report):

- Reviewed 5 SWPPPs
- General enforcement
- Issued 13 Notices of Violation
- Monitored weather patterns and storms in the Pacific through the National Weather Service

The costs presented in Table B-1 for the construction category include all of these activities and does not solely represent the cost for inspections. This should be considered when comparing the normalized cost per inspection for the city of Encinitas to other cities.

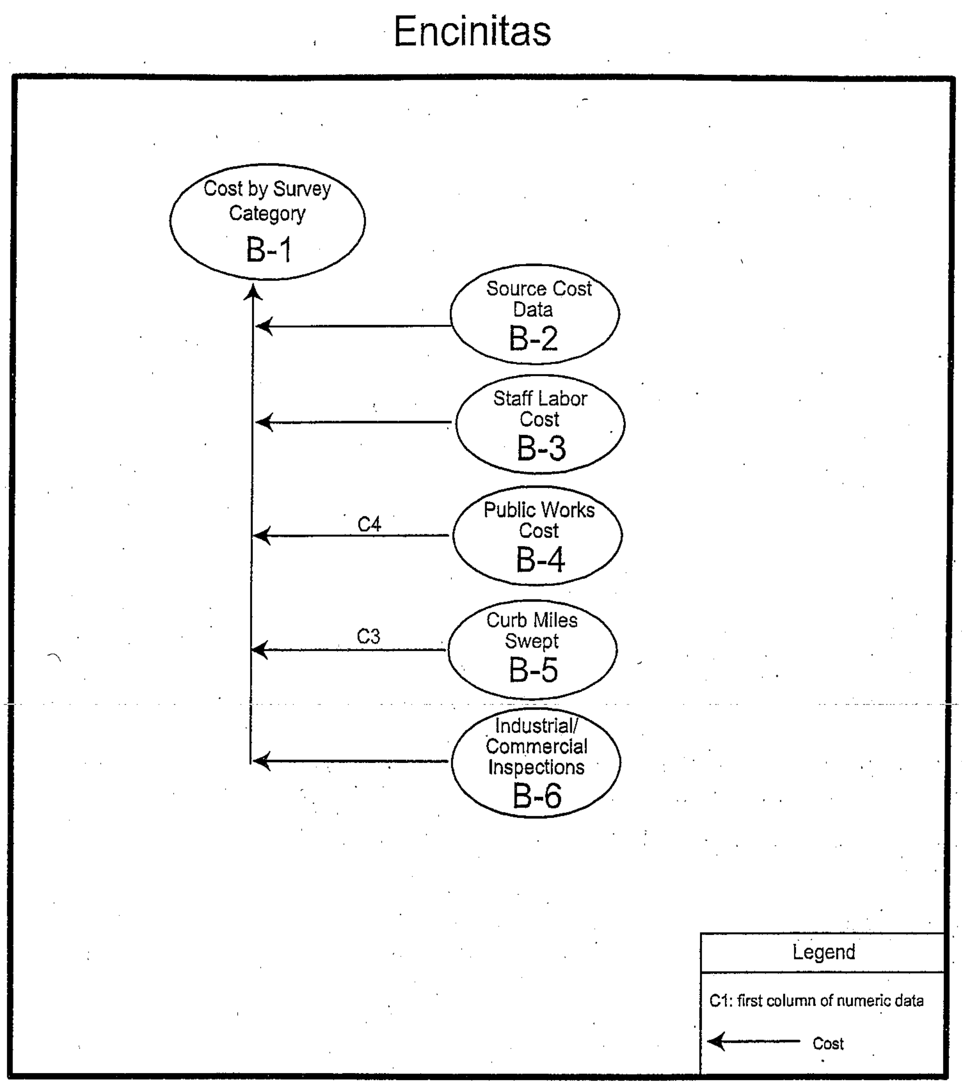


**Figure B-1. Encinitas Flowchart of Cost Tables**

### *Illicit Discharge Detection and Elimination (IDDE)*

The total cost of this category was $49,378. The IDDE program was implemented by the stormwater staff. The program consists of dry weather monitoring, investigating complaints, and looking for illicit connections during regular inspections and visual inspections of the MS4 (Encinitas, 2003b). The number of inspections for the IDDE program was not available because city staff did not have a formal inspection program. However, 76 "complaints" were filed by city staff from the informal visual inspections. Another 96 complaints were received via the city's stormwater hotline. There were 172 follow up actions to these complaints. (Encinitas, 2003b).

Consequently, cost is normalized by dividing the total cost of the category by the number of follow-up activities resulting in a normalized cost of $287 per follow-up action.

### Industrial and Commercial Management Programs

The total cost of this category was $65,596. Costs for this category included consultant administration services and costs for inspections. During 2002/2003, the city performed 266 industrial and commercial inspections (Table B-6). The normalized cost per inspection was $247. The city is planning on increasing inspections to 400 per year (Weldon, pers. comm., 4/2/04), which means this cost will significantly increase. Monitoring is performed at each industrial facility on an on-going basis (Encinitas, 2003b). Activities performed by the stormwater staff relating to the commercial component of this category are as follows (descriptions obtained from the annual stormwater report):

- Updated commercial facility inventory
- Provided BMP manuals and guidance
- Educated facility staff in regard to stormwater requirements and minimum BMPs
- Began development of a grease program
- Issued several enforcement actions

The costs presented in Table B-1 for this category include the cost for all of these activities and do not solely represent the cost for inspections. This should be considered when comparing the normalized cost per inspection for the city of Encinitas to other cities.

### Overall Stormwater Program Management

The total cost of this category was $128,159. The city had a cost of $35,000 for developing a stormwater fee. The other activities in this category were for annual reporting and legal support for developing ordinances and plaintiff attorney fees.

### Pollution Prevention and Good Housekeeping for Municipal Operations

The total cost of this category was $528,252. The largest cost of this category was street sweeping, which cost $117,962. Drain line and channel cleaning cost was $114,711 while sump, inlet, and manhole cleaning cost was $258,113. Additional activities performed were as follows (descriptions obtained from annual stormwater report):

- Engineering services for oversight, strategic planning, and management
- Trash pick-up
- Disposal of sediment
- Performed capital projects
- Updated municipal inventory

Tables B-1 and B-4 contain a breakdown of costs.

### *Post Construction Stormwater Management in New Development and Redevelopment*

The total cost for this category was $15,344. This cost includes storm drain insert installation and maintenance costs (Weldon, pers. comm., 4/2/04). Also, professional services for UV consulting, administration, report preparation, and presentations were acquired in regard to the Moonlight Beach project.

### *Public Education and Outreach and Public Involvement and Participation*

The total cost of these categories was $41,898. These categories were combined for the city of Encinitas due to major overlap between the two. All direct costs came directly from the data in Tables B-2 and B-4. Statistics were only available for the number of posters distributed. Activities in this category included the following (descriptions obtained from annual stormwater report):

- Dissemination of general stormwater brochures
- Stencils placed at all inlets
- Updated city website with stormwater related information
- Dissemination of door hangers
- Design, purchase, and dissemination of promotional key chains
- Dissemination of pens
- Published 9 local newspaper articles with information regarding the city's Clean Water Program and its accomplishments
- Production and dissemination of a general stormwater poster at public events
- Training of city staff
- Made two presentations to the city council and public attendees; an estimated 20 people were present at each meeting
- Printed materials were provided to contractors and developers via brochures
- Held a 2-hour construction workshop to inform the construction and development community about stormwater regulations and BMP requirements; 50 people attended
- Sent two special mailings relating to stormwater issues were sent to developers and contractors
- Special mailers were sent to restaurants and automotive businesses
- Held a workshop with the local nursery constituency to present nursery BMPs
- Held "garden care" type workshops; approximately 46 people attended
- Performed stormwater sampling with a $5^{th}$ grade class and made a presentation

- Presented the watershed model to a 3rd grade class; approximately 200 children participated in the presentation
- Initiated a collaborative workgroup of several cities in the North County to develop educational outreach products and approaches on a watershed basis
- Held commercial business workshops
- Participated in a public opinion survey
- Held several community events

### Water Quality Monitoring

The total cost for this category was $76,262. Costs were not normalized because they vary according to type of water quality analysis performed.

### Watershed Management

The total cost for this category was $12,400. These costs consisted of watershed plan development costs and stormwater staff labor costs.

### References

City of Encinitas, 2003. "City of Encinitas Stormwater Annual Report" 2003

Table B-1. Encinitas Cost Organized by Cost Survey Category

Cost Survey Categories

*Activity Description*

**Construction Site Stormwater Runoff Control**

| Description | External Contract | Relation to Permit[a] | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Construction inspections* | | New | 150,000.00 | Table B-2, Item 28 | 88.4% | 401 | inspections | Encinitas 2003b | 374.06 | $/inspection |
| *Allocated labor* | | New | 19,751.20 | Table B-3 | 11.6% | | | | | |
| Total | | | 169,751.20 | | 15.6% | of total stormwater cost | | | | |

| Overall Cost Category Normalizations | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|
| total category $ per inspection | 401 | inspections | Encinitas 2003b | 423.32 | total $/inspection |
| total category $ per active construction site | 40 | active construction sites | Encinitas 2003b | 4,243.78 | total $/active construction site |

**Illicit Discharge Detection and Elimination**

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Allocated labor* | | New | 49,378.00 | Table B-3 | 100.0% | 172 | follow-up activities | Encinitas 2003b | 287.08 | $/follow-up activity |
| Total | | | 49,378.00 | | 4.5% | of total stormwater cost | | | | |

**Industrial and Commercial Management Programs**

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| Inspections | | | | | | 266 | inspections | Table B-6 | 246.60 | $/inspection |
| *D-Max* | x | New | 43,600.00 | Table B-2, Item 13 | 66.5% | | | | | |
| *Ashford Engineering* | x | New | 12,120.00 | Table B-2, Item 14 | 18.5% | | | | | |
| *Allocated labor* | | New | 9,875.60 | Table B-3 | 15.1% | | | | | |
| Total | | | 65,595.60 | | 6.0% | of total stormwater cost | | | | |

**Overall Stormwater Program Management**

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Annual reporting (ashford)* | x | New | 25,080.00 | Table B-2, Item 23 | 19.6% | | | | | |
| *Storm water fee development* | | New | 35,000.00 | Table B-2, Item 29 | 27.3% | | | | | |
| *Miscellaneous* | | New | 520.73 | Table B-2, Item 27 | 0.4% | | | | | |
| *NPDES fee* | | New | 3,750.00 | Table B-2, Item 5 | 2.9% | | | | | |
| *Legal fees-ordinances* | x | New | 11,915.50 | Table B-2, Item 25 | 9.3% | | | | | |
| *Legal fees-plaintiff attorneys* | x | New | 9,950.00 | Table B-2, Item 26 | 7.8% | | | | | |
| *Grant writing* | | New | 2,440.00 | Table B-2, Item 24 | 1.9% | | | | | |
| *Allocated labor* | | New | 39,502.40 | Table B-3 | 30.8% | | | | | |
| Total | | | 128,158.63 | | 11.8% | of total stormwater cost | | | | |

**Pollution Prevention and Good Housekeeping for Municipal Operations**

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Ashford Engineering* | x | New | 8,840.00 | Table B-2, Item 7 | 1.7% | 4 | inspections | Encinitas 2003b | 2,210.00 | $/inspection |
| *Trash pick-up* | | Existing | 2,850.00 | Table B-2, Item 12 | 0.5% | | | | | |
| *Trash pick-up (public works)* | | Existing | 13,400.00 | Table B-4 | 2.5% | | | | | |
| *Disposal of sediment* | | New | 2,500.00 | Table B-2, Item 8 | 0.5% | | | | | |
| *Allocated labor* | | New | 9,875.60 | Table B-3 | 1.9% | | | | | |
| *Sumps, inlets, manholes* | | Enhanced | 258,113.00 | Table B-4 | 48.9% | | | | | |
| *Drain lines and channels* | | Enhanced | 114,711.00 | Table B-4 | 21.7% | | | | | |
| *Street sweeping* | | Enhanced | 117,962.00 | Table B-4 | 22.3% | 5,832 | curb miles swept | Table B-5 | 20.23 | $/curb mile swept |
| Total | | | 528,251.60 | | 48.6% | of total stormwater cost | | | | |



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**Table B-1. Continued.**

### Post Construction Water Management in New Development and Redevelopment

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Overall Storm Drain Inserts Maintenance* | | | | | | 16 | inserts installed | Encinitas, 2003b | 119.25 | $/insert installed |
| *Storm drain inserts* | | New | 1,240.00 | Table B-2, Item 9 | 8.1% | | | | | |
| *Storm drain inserts* | | New | 668.01 | Table B-2, Item 10 | 4.4% | | | | | |
| *Ashford Engineering (moonlight)* | x | New | 3,560.00 | Table B-2, Item 11 | 23.2% | | | | | |
| *Allocated labor* | | New | 9,875.60 | Table B-3 | 64.4% | | | | | |
| Total | | | 15,343.61 | | 1.4% | of total stormwater cost | | | | |

### Public Education, Outreach, Involvement, and Participation

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Surveys and posters* | | New | 3,292.47 | Table B-2, Item 20 | 7.9% | | | | | |
| *Surveys and posters* | | New | 2,000.00 | Table B-2, Item 21 | 4.8% | | | | | |
| *UC Extension workshop with nurseries.* | | New | 2,374.00 | Table B-2, Item 15 | 5.7% | | | | | |
| *Ashford engineering* | x | New | 14,480.00 | Table B-2, Item 22 | 34.6% | | | | | |
| *Allocated labor* | | New | 19,751.20 | Table B-3 | 47.1% | | | | | |
| Total | | | 41,897.67 | | 3.9% | of total stormwater cost | | | | |

### Water Quality Monitoring

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Wet weather monitoring* | | New | 25,186.00 | Table B-2, Item 6 | 33.0% | | | | | |
| *ICID dry weather monitoring* | | New | 14,893.00 | Table B-2, Item 16 | 19.5% | | | | | |
| *ICID dry weather monitoring* | | New | 3,161.00 | Table B-2, Item 17 | 4.1% | | | | | |
| *ICID dry weather monitoring* | | New | 3,395.00 | Table B-2, Item 18 | 4.5% | | | | | |
| *Allocated labor* | | New | 29,626.80 | Table B-3 | 38.8% | | | | | |
| Total | | | 76,261.80 | | 7.0% | of total stormwater cost | | | | |

### Watershed Management

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Watershed plan development* | | New | 2,524.00 | Table B-2, Item 19 | 20.4% | | | | | |
| *Allocated labor* | | New | 9,875.60 | Table B-3 | 79.6% | | | | | |
| Total | | | 12,399.60 | | 1.1% | of total stormwater cost | | | | |

| | |
|---|---|
| Total stormwater costs | 1,087,037.71 |

a. This column indicates whether required activities were being performed prior to stormwater permits. In some cases activities were enhanced due to permit requirements.

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Table B-2. Source Data Table Submitted by City of Encinitas (cost survey categories added)

| Item # | City of Encinitas Category | Cost | | Cost Survey Category[1] |
|---|---|---|---|---|
| 1 | Staff Salary | 147,760.00 | | See Table B-3 |
| 2 | Contract Staff | 41,743.00 | | See Table B-3 |
| 3 | Supplies/Travel/Equipment | 5,409.00 | | See Table B-3 |
| 4 | Vehicle | 2,600.00 | | See Table B-3 |
| | Permit Fees: | | | |
| 5 | State Water Resources Control Board | 3,750.00 | | Management |
| 6 | Copermittee MOU Fees | 25,186.00 | | Monitoring |
| | Municipal Programs: | | | |
| | Miscellaneous Contracting | | | |
| 7 | Ashford Engineering | 8,840.00 | | Pollution Prevention |
| 8 | AMEC | 2,500.00 | | Pollution Prevention |
| 9 | BMP Implementation & Maintenance | 1,240.00 | | Post Construction |
| 10 | Downstream Services | 668.01 | | Post Construction |
| 11 | Ashford Engineering (Moonlight) | 3,560.00 | | Post Construction |
| 12 | Clean Up/Abatement Programs | 2,850.00 | | Pollution Prevention |
| | Industrial/Commercial Programs: | | | |
| | Inspections | | | |
| 13 | D-Max | 43,600.00 | | Industrial |
| 14 | Ashford Engineering | 12,120.00 | | Industrial |
| | Nursery Program: | | | |
| | Inspections | | | |
| 15 | Education Activities (UC Regents) | 2,374.00 | | Public Education |
| | Construction Programs: | 0.00 | | |
| | IC/ID Program: | | | |
| | Source Tracking/Spills/Inspections | 0.00 | | |
| | Water Quality Monitoring: | | | |
| 16 | Encina | 14,893.00 | | Monitoring |
| 17 | Del Mar Analytical | 3,161.00 | | Monitoring |
| 18 | San Elijo JPA | 3,395.00 | | Monitoring |
| | Watershed Urban Runoff Management: | | | |
| 19 | Ashford Engineering | 2,524.00 | 2 | Watershed |
| 20 | City of Oceanside (survey& posters) | 3,292.47 | | Public Education |
| 21 | City of Carlsbad (survey) | 2,000.00 | | Public Education |
| | Education: | | | |
| 22 | Ashford Engineering | 14,480.00 | | Public Education |
| | Reporting (JURMP/WURMP Annual Report): | | | |
| 23 | Ashford Engineering | 25,080.00 | | Management |
| 24 | Grant Writing: | 2,440.00 | | Management |
| | Legal Fees: | | | |
| 25 | Glenn Sabine | 11,915.50 | | Management |
| 26 | Marco Gonzalez | 9,950.00 | | Management |
| 27 | Misc.: BMP Cottonwood Creek & San Elijo Outlet | 520.73 | | Management |
| 28 | Construction | 150,000.00 | | Construction |
| 29 | Appropriation for Stormwater Fee Vote | 35,000.00 | 3 | Management |
| 30 | B&D Construction | 35,887.00 | 4 | Unallocated |
| | Total Expenditures | 618,738.71 | | |

(Source: Weldon, pers. comm., 4/2/04)

1. Cost Categories Abbreviated According to the Following:
   Construction: Construction Site Stormwater Runoff Control
   Illicit Discharge: Illicit Discharge Detection and Elimination
   Industrial: Industrial and Commercial Management Programs
   Management: Overall Stormwater Program Management

**Table B-2. Continued.**

Pollution Prevention: Pollution Prevention and Good Housekeeping for Municipal Operations
Post Construction: Post Construction Water Management in New Development and Redevelopment
Public Education: Public Education, Outreach, Involvement, and Participation
Monitoring: Water Quality Monitoring
Watershed: Watershed Management

2. Per personal communication with Kathy Weldon, this number was reduced to $2,524 from $12,880.
3. Per personal communication with Meleah Ashford, this number was reduced to $35,000 from $100,000.
4. Construction of storm drain was not attibuted to permit compliance.

**Table B-3. Distribution of Labor ($189,503) and Supplies/Travel/Equipment/Vehicle ($8,009) Costs Submitted by City of Encinitas Staff**

| Category | Percent All Clean Water Program Staff | Cost Allocated by Percentages |
|---|---|---|
| Public Outreach | 5% | 9,875.60 |
| Public Involvement | 5% | 9,875.60 |
| ICID | 25% | 49,378.00 |
| Construction | 10% | 19,751.20 |
| Post Construction (SUSMP) | 5% | 9,875.60 |
| Industrial | 5% | 9,875.60 |
| Pollution Prevention for Municipal | 5% | 9,875.60 |
| Monitoring | 15% | 29,626.80 |
| Overall Stormwater Management | 20% | 39,502.40 |
| Watershed Management | 5% | 9,875.60 |
| Total | 100% | 197,512.00 |

(Source: Ashford, pers. comm., 4/15/04)

**Table B-4. Public Works Cost Data Submitted by City of Encinitas Staff**

| Description | Labor | Cost Type<br>Equipment | Contract | Total |
|---|---|---|---|---|
| Sumps, inlets, manholes | 101,404.00 | 72,968.00 | 83,741.00 | 258,113.00 |
| Drain lines and channels | 101,405.00 | 13,306.00 | 0.00 | 114,711.00 |
| Trash pick-up | 0.00 | 0.00 | 13,400.00 | 13,400.00 |
| Street sweeping | 0.00 | 0.00 | 117,962.00 | 117,962.00 |
| Total | 202,809.00 | 86,274.00 | 215,103.00 | 504,186.00 |

(Source: Ashford, pers. comm., 4/15/04)

**Table B-5. Calculation of Number of Curb Miles Swept**

| Street Miles Swept | Frequency (yearly) | Reference | Annual Street Miles Swept | Annual Curb Miles Swept[1] |
|---|---|---|---|---|
| 243 | 12 | Encinitas, 2003b | 2,916 | 5,832 |

1. Calculated by multiplying the "annual street miles swept" by 2.

**Table B-6. Calculation of Industrial/Commercial Inspections**

| Type | Number | Reference |
|---|---|---|
| Industrial | 3 | Encinitas, 2003b |
| Commercial (DMAX) | 202 | Encinitas, 2003b |
| Commercial, nurseries | 5 | Encinitas, 2003b |
| Complaint driven (Ashford) | 56 | Encinitas, 2003b |
| Total | 266 | |

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The backup calculations for the cost for each cost survey category in Section 5 and the sources of the cost data are presented in this appendix. Tables generally are presented by sequentially increasing levels of detail. Figure C-1 illustrates how data is shared throughout the tables.

Table C-1 contains all costs organized into the various standard cost survey categories. The subtotals for each cost category are also presented in Section 5, Table 5-2. The remaining tables (C-2 through C-5) present the detailed back-up information for the numbers in Table C-1. Table C-1 is linked to the back-up tables by the table and item numbers in the 'Source' column. Most of the cost information provided by city staff is listed in Table C-2. Item numbers corresponding to the subtotals in Table C-2 were added to the left hand column to easily show how the numbers are pulled forward to Table C-1. The right hand column in Table C-2 was added to show how costs were allocated to the cost survey categories. Table C-1 entries that were not taken directly from Table C-2 are found in Tables C-3 through C-5.

Table C-1 also provides statistics describing the level of effort for certain activities by numerically representing what or how much was accomplished. References are provided within Table C-1 for the activity statistics. Where relevant statistics are available, normalized costs are calculated in Table C-1. Normalized costs are calculated by dividing the cost of the category or activity by the activity statistic.

For the city of Fremont, labor costs of the stormwater staff are not distributed among the various survey categories. Instead, it is all captured under Overall Stormwater Program Management. Thus, comparing costs with other municipalities where such costs are distributed, Fremont's Overall Stormwater Management Program costs will be higher.

The Union Sanitation District (USD) is under contract with the city of Fremont to provide facility and illicit discharge services, construction inspections, public education, countywide clean water program meeting participation, reports, database, and vehicles. The breakdown of the USD cost is presented in Table C-4.

The contribution made to the Alameda County Clean Water Program (ACCWP) was allocated according to Table C-5. Table C-5 has the total cost of the ACCWP broken into stormwater program categories. ACCWP supports subcommittee meetings, legal advice, regulatory advice, agency education and information sharing. On the bottom of the table is the dollar amounts contributed from each of the participating agencies. Fremont contributed $339,990 out of the total ACCWP expenses of $2,342,113. The ratio of Fremont contribution to the total ACCWP program cost was used to determine the contribution Fremont made to the individual programs. This calculation is in the far right column of Table C-5.

Detailed descriptions of how the costs were developed are contained in the following paragraphs.

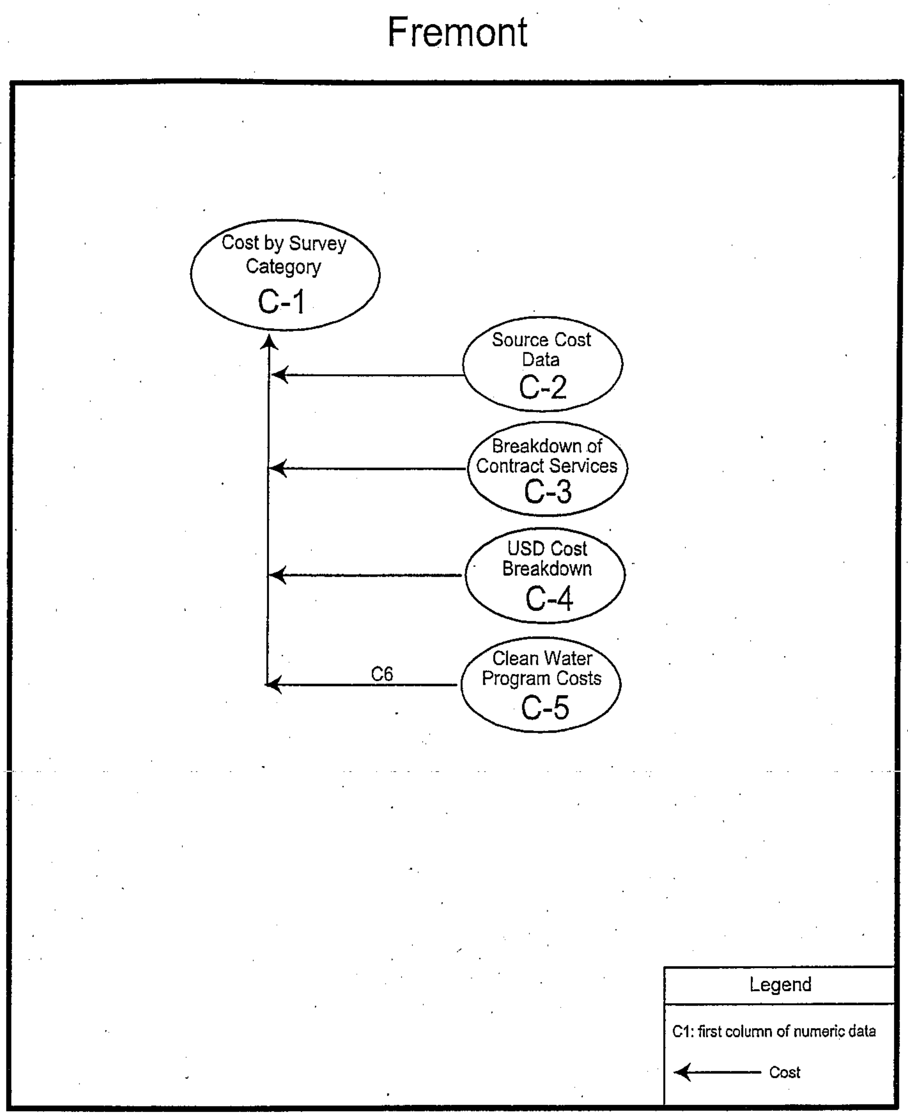


**Figure C-1. Fremont Flowchart**

## *Construction Site Stormwater Runoff Control*

The total cost of this category was $17,715. The costs of this category were for inspection of active construction sites and for plan checking to verify appropriate post construction BMPs were being used (Fremont, 2003b). Employee training and 58 erosion control inspections were conducted (Fremont, 2003b). USD performed 139 general stormwater inspections.

## *Illicit Discharge Detection and Elimination (IDDE)*

The total cost of this category was $5,917. All of the costs in this category represent contributions to the ACCWP for assistance in eliminating non-stormwater discharges, analyzing findings, reporting, and staff labor. During the year, 118 follow-up activities were conducted (Fremont, 2003b).

### *Industrial and Commercial Management Programs*

The total cost of this category was $210,027. Most of the activities for this category were performed by USD. A cost breakdown by activity was not provided. The total number of inspections was 482, which includes 91 re-inspections. The city had 81 enforcement actions in 2002/03 and identified and abated 32 "Potential Exposure" and 18 "Non-Stormwater" discharges. (Fremont, 2003b). Inspection documentation costs amounted to $31,697. Though USD also performed some construction inspections, this cost was included here because the majority of inspections were for the industrial/commercial program. Inspection costs were $160,861 resulting in a cost of $436/inspection.

Contributions to the ACCWP totaled $17,469 and were for outreach, refining guidelines, training, and reporting.

### *Overall Stormwater Program Management*

The total cost of this category was $453,872. Sixty-nine percent of the cost allocated to this category was for the stormwater staff labor and allocation of overhead cost. The city staff was unable to distribute the labor costs among the survey categories. Other costs in this category were for USD services, NPDES fees, consultant services, and various administrative costs. USD staff participated in ACCWP subcommittees at a cost of $12,928, $7,659 in reporting costs, $6,107 for meeting attendance, and $135 for mitigation work. The mitigation work was a minor cost and therefore allocated to this cost category rather than investigate for a description of the work.

Contributions to the ACCWP totaled $95,560 and were for regulatory advising, instituting improvements, support committees, legal advice, website, newsletters, dues, permit fees, business water quality incentives, miscellaneous expenses, and staff labor.

### *Pollution Prevention and Good Housekeeping for Municipal Operations*

The total cost of this category was $2,128,175. Of this amount, 85 percent was for street sweeping. The costs for this category were for the activities of street sweeping, litter/debris removal, and GIS. The city performed other activities but was unable to provide the associated costs. These activities were cleaning drain lines and channels, inlets, cross culverts, and conduits (Silva, pers. comm., 9/22/04). Additional activities obtained from the annual stormwater report included employee training, maintenance staff attendance at maintenance subcommittee meetings, mailing information packets to new businesses, workshops, partnered with USD to develop, print, and mail a newsletter (Fremont, 2003b).

Contributions to the ACCWP totaled $13,175 and were for performance standard development and updating, and staff labor.

### Post Construction Stormwater Management in New Development and Redevelopment

The total cost of this category was $19,746. This cost was for engineering, planning, and city staff to research, track, and report information for the annual stormwater report. It was also for task force meetings to develop strategies for compliance with their permit regarding new development and redevelopment. The source table (C-2) describes this cost as a "quasi-external expenditure" because it is the amount that was transferred to engineering and other departments to cover stormwater related activities.

Contributions to the ACCWP totaled $15,337 and were for controls guidance, watershed inventory, construction activities, performance standards, coordination, brochures, and staff labor.

### Public Education and Outreach and Public Involvement and Participation

The total cost allocated to these categories was $101,717. Advertising costs (including billboards and newsletters) were for public education and outreach. Creek clean-up had both public involvement, participation, and outreach components. Due to this overlap, the programs were combined for the city of Fremont. Approximately 70 percent of the creek clean-up was done by city staff and volunteers accounted for 30 percent of the effort (Silva, pers. comm., 9/22/04). Other activities in these categories included the following (descriptions obtained from the annual stormwater report):

- 24 school outreach presentations to 5th grade classrooms
- 4 school outreach presentations at middle school "special day" classes
- Stormwater staff participated in a Safety Fair at Gomez Elementary by doing a watershed demonstration and distributing pamphlets
- Stormwater staff participated in several public events including the Fremont Festival of the Arts, Good Neighbor Day, Boston Scientific Health and Wellness Fair, and National Night Out
- Rock Steady Juggling performance to 1,490 students who were educated about urban runoff issues
- Educated 680 students about urban runoff issues at the Caterpillar Puppet show
- Participated in and helped fund the "Kids in Creek" workshops
- A city of Fremont staff member served as a panelist at California State University Hayward's "Careers in the Environmental Sciences". The staff member discussed career opportunities in the stormwater field with students.
- Distributed brochures and fliers to Devry University
- The city of Fremont Environmental Services Department funded Math/Science Nucleus (MSN) and city of Fremont Park and Recreation Department to develop and lead field trips to educate 140 students and 26 parents about urban runoff issues. The city also

funded Irvington Academy High School to educate students about urban runoff issues. (Fremont, 2003)

USD provided $25,897 worth of public education services, accounting for 51 percent of the cost in this category. USD provides a website with BMP fact sheets for citizens and business owners and participates in school outreach activities. The materials promote Integrated Pest Management and the Bay Area-wide campaign called Our Water/Our World. USD also provides brochures and facility inspection checklists for businesses such as restaurants and printer shops.

Contributions to the ACCWP totaled $50,796 and were for effectiveness evaluations, staff training, implementation assistance, educational outreach for organized activities and events, community stewardship grants, elementary education, environmental education at a fair, and staff labor.

### *Water Quality Monitoring*

The total cost of this category was $131,326. Of this cost, $7,200 was for water quality sampling at two locations. Both chronic and acute toxicity tests were performed (Silva, pers. comm., 9/22/04).

Contributions to the ACCWP totaled $124,126 and were for regional state board annual fees, mercury testing, watershed inventory, data management, GIS assistance, fishery assessment, contract recreation, litter and leaf control, TMDL compliance tasks, diazinon grant, analytical services, a monitoring project, and staff labor.

### *Watershed Management*

The total cost of this category was $17,610. All of the costs in this category represent contributions to the ACCWP for development of a watershed study framework, assessment of pilot project activities, and staff labor.

### *References*

City of Fremont, 2003. "Alameda Countywide Clean Water Program Fiscal Year 2002/03 Annual Report". Volume III of IV.

**Table C- 1. Fremont Cost Organized by Cost Survey Category**

Cost Survey Categories

*Activity Description*

### Construction Site Stormwater Runoff Control

| Description | External Contract | Relation to Permit[a] | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Construction inspections by USD* | | New | 17,715 | Table C-4 | 100% | 197 | inspections[b] | Fremont, 2004b | 89.93 | $/inspection |
| Total | | | 17,715 | | 0.6% | of total stormwater cost | | | | |

### Illicit Discharge Detection and Elimination

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Assistance to eliminate non-stormwater discharges, analyze findings, reporting* | | New | 5,081 | Table C-5, Item 8.1 | 85.9% | | | | | |
| *Staff labor (including overhead)* | | New | 836 | Table C-5, Item 8.2 | 14.1% | | | | | |
| Total | | | 5,917 | | 0.2% | of total stormwater cost | | | | |

### Industrial and Commercial Management Programs

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Business inspection* | | New | 160,861 | Table C-4 | 76.6% | 482 | inspections | Silva, pers. comm. 9/22/04 | 333.74 | $/inspection |
| *Inspection documentation* | | New | 31,697 | Table C-4 | 15.1% | | | | | |
| *Inspections, outreach activity, track findings, refine guidelines, training, reporting* | | New | 16,694 | Table C-5, Item 9.1 | 7.9% | | | | | |
| *Staff labor (including overhead)* | | New | 775 | Table C-5, Item 9.2 | 0.4% | | | | | |
| Total | | | 210,027 | | 6.8% | of total stormwater cost | | | | |
| Overall Cost Category Normalizations | | | | | | | | | | |
| total category $ per inspection | | | | | | 482 | inspections | Silva, pers. comm. 9/22/04 | 435.74 | total $/inspection |

### Overall Stormwater Program Management

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Labor for city stormwater staff* | | New | 171,047 | Table C-2, Items 1,2,3, and 4 | 37.7% | | | | | |
| *Office supplies* | | New | 558 | Table C-2, item 7 | 0.1% | | | | | |
| *Periodicals* | | New | 469 | Table C-2, item 8 | 0.1% | | | | | |
| *Printing* | | New | 1,688 | Table C-2, item 9 | 0.4% | | | | | |
| *Collection fee* | | New | 11,777 | Table C-2, Item 11 | 2.6% | | | | | |
| *NPDES fee* | | New | 8,750 | Table C-2, Item 16 | 1.9% | | | | | |
| *Telephone* | | New | 13 | Table C-2, item 19 | 0.0% | | | | | |
| *Postage* | | New | 75 | Table C-2, item 20 | 0.0% | | | | | |
| *Travel expenses* | | New | 403 | Table C-2, item 21 | 0.1% | | | | | |
| *Training* | | New | 840 | Table C-2, item 22 | 0.2% | | | | | |
| *Technical training* | | New | 1,750 | Table C-2, item 23 | 0.4% | | | | | |
| *Office machines<$5k* | | New | 350 | Table C-2, item 28 | 0.1% | | | | | |
| *Informational systems* | | New | 19,375 | Table C-2, Item 33 | 4.3% | | | | | |
| *Worker's comp* | | New | 590 | Table C-2, item 34 | 0.1% | | | | | |
| *General liability* | | New | 3,058 | Table C-2, item 35 | 0.7% | | | | | |
| *Overhead allocation* | | New | 110,737 | Table C-2, Item 37 | 24.4% | | | | | |
| *ACCWP participation* | | New | 12,928 | Table C-4 | 2.8% | | | | | |
| *Reporting* | | New | 7,659 | Table C-4 | 1.7% | | | | | |
| *Meeting* | | New | 6,107 | Table C-4 | 1.3% | | | | | |
| *Mitigation* | | New | 136 | Table C-4 | 0.0% | | | | | |
| *Regulatory advising, institute improvements, support committees, legal advice, website, and newsletter* | | New | 32,372 | Table C-5, Item 2.1 | 7.1% | | | | | |

Table C – 1. Continued.

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| Dues for regional stormwater representation groups and tasks of regional benefit | | New | 10,887 | Table C-5, Item 2.2 | 2.4% | | | | | |
| NPDES permit fee (ACCWP) | | New | 2,903 | Table C-5, Item 2.3 | 0.6% | | | | | |
| Program contingency | | New | 10,670 | Table C-5, Item 2.4 | 2.4% | | | | | |
| Contribution to support business-water quality incentives program | | New | 2,903 | Table C-5, Item 2.5 | 0.6% | | | | | |
| Miscellaneous | | New | 5,081 | Table C-5, Item 2.6 | 1.1% | | | | | |
| Staff labor for ACCWP (including overhead) | | New | 30,745 | Table C-5, Item 2.8 | 6.8% | | | | | |
| Total | | | 453,872 | | 14.6% | of total stormwater cost | | | | |

Pollution Prevention and Good Housekeeping for Municipal Operations

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| Street Sweeping Program | | | | | | 31,405 | curb miles swept | Silva, pers. comm., 9/22/04 | 60.98 | $/curb mile swept |
| Street sweeping | | Enhanced | 115,000 | Table C-2, Item 30 | 5.4% | | | | | |
| Street sweeping | | Enhanced | 1,800,000 | Table C-2, Item 31 | 84.6% | | | | | |
| Litter/debris removal | | Existing | 200,000 | Table C-2, Item 32 | 9.4% | | | | | |
| Performance standard updating and development | | New | 12,339 | Table C-5, Item 6.1 | 0.6% | | | | | |
| Staff labor (including overhead) | | Enhanced | 836 | Table C-5, Item 6.2 | 0.0% | | | | | |
| Total | | | 2,128,175 | | 68.6% | of total stormwater cost | | | | |

Table C1 continued

Post Construction Stormwater Management in New Development and Redevelopment

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| Quasi external expenditure | | New | 19,746 | Table C-2, Item 36 | 56.3% | | | | | |
| Controls guidance, watershed inventory, consruction activities, performance standards, coordination | | New | 11,613 | Table C-5, Item 7.1 | 33.1% | | | | | |
| Reprographic services (brochures) | | New | 2,177 | Table C-5, Item 7.2 | 6.2% | | | | | |
| Staff labor (including overhead) | | New | 1,546 | Table C-5, Item 7.3 | 4.4% | | | | | |
| Total | | | 35,083 | | 1.1% | of total stormwater cost | | | | |

Public Education, Outreach, Involvement, and Participation

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| Creek clean-up | | New | 5,200 | Table C-2, Item 6 | 5.1% | | | | | |
| Advertising | | New | 310 | Table C-2, Item 24 | 0.3% | | | | | |
| Storage space rental | | New | 210 | Table C-2, Item 25 | 0.2% | | | | | |
| Math Science Nucleus (MSN) Environmental Education | | New | 6,803 | Table C-3 | 6.7% | | | | | |
| Citywide newsletter | | New | 12,500 | Table C-3 | 12.3% | | | | | |
| Public Education | | New | 25,897 | Table C-4 | 25.5% | | | | | |
| Effectiveness evaluation, staff training, implemenation assistance | | New | 6,532 | Table C-5, Item 5.2 | 6.4% | | | | | |
| Educational outreach for organized activities and events | | New | 4,355 | Table C-5, Item 5.3 | 4.3% | | | | | |
| Community stewardship grants, implementation assistance | | New | 13,282 | Table C-5, Item 5.4 | 13.1% | | | | | |
| Baysavers elementary education curriculum and implemenation | | New | 8,129 | Table C-5, Item 5.5 | 8.0% | | | | | |
| Bay area environmental education resource fair | | New | 363 | Table C-5, Item 5.6 | 0.4% | | | | | |
| General outreach | | New | 7,258 | Table C-5, Item 5.7 | 7.1% | | | | | |
| Staff labor (including overhead) | | New | 10,876 | Table C-5, Item 5.8 | 10.7% | | | | | |
| Total | | | 101,717 | | 3.3% | of total stormwater cost | | | | |

**Table C – 1. Continued.**

**Water Quality Monitoring**

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Water quality sampling* | | New | 7,200 | Table C-3 | 5.5% | | | | | |
| *Regional state board annual fee* | | New | 20,323 | Table C-5, Item 4.1 | 15.5% | | | | | |
| *Murcury testing* | | New | 9,436 | Table C-5, Item 4.2 | 7.2% | | | | | |
| *Watershed inventory, data management, and GIS asstistance* | | New | 20,323 | Table C-5, Item 4.3 | 15.5% | | | | | |
| *Fishery assessment, contract recreation, litter and leaf control* | | New | 18,871 | Table C-5, Item 4.4 | 14.4% | | | | | |
| *Contribution to TMDL compliance tasks* | | New | 23,226 | Table C-5, Item 4.5 | 17.7% | | | | | |
| *Diazinon grant* | | New | 1,452 | Table C-5, Item 4.6 | 1.1% | | | | | |
| *Analytical services* | | New | 6,678 | Table C-5, Item 4.7 | 5.1% | | | | | |
| *Monitoring project* | | New | 5,807 | Table C-5, Item 4.8 | 4.4% | | | | | |
| *Staff labor (inlcuding overhead)* | | New | 18,011 | Table C-5, Item 4.10 | 13.7% | | | | | |
| Total | | | 131,326 | | 4.2% | of total stormwater cost | | | | |

**Watershed Management**

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Development of watershed study framework, assessment of pilot project activities* | | New | 9,435.65 | Table C-5, Item 3.2 | 53.6% | | | | | |
| *Staff labor (including overhead)* | | New | 8,173.96 | Table C-5, Item 3.4 | 46.4% | | | | | |
| Total | | | 17,609.60 | | 0.6% | of total stormwater cost | | | | |

| | |
|---|---|
| **Total Stormwater Costs.** | 3,101,442 |

a. This column indicates whether required activities were being performed prior to stormwater permits. In some cases activities were enhanced due to permit requirements.
b. Inspections for construction includes 58 erosion control inspections and 157 construction site inspections.

**Table C-2. Source Data Table Submitted by City of Fremont (cost survey categories added)**

| Item # | City of Fremont Category | Total Cost | Cost Survey Category[1] |
|---|---|---|---|
| 1 | Salaries | 115,954.72 | Management |
| 2 | Benefits | 37,413.57 | Management |
| 3 | Overtime | 928.78 | Management |
| 4 | Part time salaries | 16,750.10 | Management |
| 5 | Promotional Materials | 0.00 | |
| 6 | Misc Operating Supplies | 5,199.59 | Public Education |
| 7 | Office Supplies | 558.25 | Management |
| 8 | Periodicals | 469.06 | Management |
| 9 | Printing | 1,687.98 | Management |
| 10 | Legal | 0.00 | |
| 11 | Consultant Services | 11,777.40 | Management |
| 12 | Contractual Services | 26,503.39 | See Table C-3 |
| 13 | Photographic Services | 0.00 | |
| | Governmental Services[2] | | |
| 14 | Union Sanitary District | 263,000.00 | See Table C-4 |
| 15 | Alameda Countywide Clean Water Program | 339,990.00 [3] | See Table C-5 |
| 16 | State Water Resource Control Board | 8,750.00 | Management |
| | Media Purchase/Advertising | | |
| 18 | Other Professional Services | 0.00 | |
| 19 | Telephone | 12.96 | Management |
| 20 | Postage | 75.00 | Management |
| 21 | Travel Expenses | 403.43 | Management |
| 22 | Training | 840.29 | Management |
| 23 | Technical Training | 1,750.00 | Management |
| 24 | Advertising development | 310.00 | Public Education |
| 25 | Space Rental | 210.00 | Public Education |
| 26 | Equipment Rental | 0.00 | |
| 27 | Office Machines > $5k | 0.00 | |
| 28 | Office Machines<$5k | 350.00 | Management |
| 29 | Office Furniture | 0.00 | |
| 30 | Interfund Transfers | 115,000.00 | Pollution Prevention |
| 31 | Interfund Transfers | 1,800,000.00 | Pollution Prevention |
| 32 | Interfund Transfers | 200,000.00 | Pollution Prevention |
| 33 | Info Systems | 19,375.20 | Management |
| | Transfer to Veh Repl Rund | | |
| 34 | Worker's Comp | 590.42 | Management |
| 35 | General Liability | 3,058.22 | Management |
| 36 | Quasi-External Expenditure | 19,746.31 | Post Construction |
| 37 | Overhead Allocation | 110,737.00 | Management |
| | Total | 3,101,441.67 | |

(Source: Silva, pers. comm., 4/5/04)

1. Cost Categories Abbreviated According to the Following:
   Construction: Construction Site Stormwater Runoff Control

**Table C-2. Continued.**

Illicit Discharge: Illicit Discharge Detection and Elimination
Industrial: Industrial and Commercial Management Programs
Management: Overall Stormwater Program Management
Pollution Prevention: Pollution Prevention and Good Housekeeping for Municipal Operations
Post Construction: Post Construction Water Management in New Development and Redevelopment
Public Education: Public Education, Outreach, Involvement, and Participation
Monitoring: Water Quality Monitoring
Watershed: Watershed Management

2. The original total submitted for total governmental services was $611,417. This figure was changed per email from Barbara Silva on 6/10/04 to 611,750 as shown by the breakdown between Union Sanitary District, Alameda Countywide Clean Water Program, and State Water Resource Control Board.

3. This number was adjusted down from $340,000 upon reciept of contract breakdown (see Table C-5).

**Table C-3. Breakdown of Contractual Services (Table C-2, Item 12)**

| Description | Cost | Cost Survey Category |
|---|---|---|
| Math Science Nucleus (MSN) Environmental Education | 6,803 | Public Education |
| Water quality sampling (Pacific Eco Risk) | 7,200 | Monitoring |
| Citywide newsletter | 12,500 | Public Education |
| Total | 26,503 | |

(Source: Silva, pers. comm., 4/15/04)

**Table C-4. Breakdown of Union Sanitation District (USD) Cost (Table C-2, Item 14)**

| Description | Cost | Cost Survey Category |
|---|---|---|
| Public education | 25,897 | Public Education |
| ACCWP participation | 12,928 | Management |
| Reporting | 7,659 | Management |
| Meeting | 6,107 | Management |
| Inspection documentation | 31,697 | Industrial |
| Mitigation | 136 | Management |
| Construction inspection | 17,715 | Construction |
| Business inspection | 160,861 | Industrial |
| | 263,000 | |

(Source: Silva, pers. comm., 4/15/04)

Table C-5. ACCWP Cost Breakdown

# GENERAL CLEAN WATER PROGRAM 2002-2003

**Budget Unit 50201** F15W81 PROGRAM MANAGER: Jim Scanlin

## 2. PLANNING AND REGULATORY COMPLIANCE

MAKE ENTRIES IN YELLOW BOXES

| Item | Code | Hours | Rate | | Cost | GENERAL PROGRAM AMOUNT | % of Grand Total | Fremont Contribution |
|---|---|---|---|---|---|---|---|---|
| 1 EISENBERG OLIVIERI ASSOCIATES | E01 | | | | | $223,000 | 10% | 32,372 |
| Regulatory Advising, Institute Improvements, Support Committees, Legal Advice, Website, and Newsletter | | | | | | | | |
| 2 PARTICIPATION IN REGIONAL STORMWATER EFFORTS | J11 | | | | | $75,000 | 3% | 10,887 |
| Dues for Regional Stormwater Representation Groups and tasks of regional benefit | | | | | | | | |
| 3 NPDES PERMIT FEE | J11 | | | | | $20,000 | 1% | 2,903 |
| Fee for Countywide Clean Water Program Permit - Required by Regional Water Board | | | | | | | | |
| 4 CONTINGENCY | | | | | | $73,500 | 3% | 10,670 |
| Program Contingency Amount | | | | | | | | |
| 5 GREEN BAY BUSINESS PROGRAM | J11 | | | | | $20,000 | 1% | 2,903 |
| Contribution to Support Business - Water Quality Incentives Program | | | | | | | | |
| 6 SPECIAL DEPARTMENTAL ACCOUNT | | | | | | $35,000 | 1% | 5,081 |
| Don will tell us what this covers | | | | | | | | |
| 7 CONTRACT | | | | | | $0 | 0% | 0 |
| To fulfill Total Maximum Daily Load (TMDL) requirements | | | | | | | | |
| 8 STAFF – | | | | | | $211,793 | 9% | 30,745 |
| R. HALE | J01 | 300 | 85.00 | | $25,500 | | | |
| J. SCANLIN | J02 | 1,332 | 80.00 | | $106,560 | | | |
| G. SHAWLEY | J02 | 145 | 63.00 | | $9,135 | | | |
| LABOR OVERHEAD | | | | | $70,598 | | | |
| TOTAL PROGRAM ADMINISTRATION | | | | | | $658,293 | 28% | 95,560 |
| CLEAN WATER DIV. STAFF HRS. | | 1,777 | | | | | | |

## 3. FOCUSED WATERSHED STUDIES

| Item | Code | Hours | Rate | | Cost | GENERAL PROGRAM AMOUNT | % of Grand Total | Fremont Contribution |
|---|---|---|---|---|---|---|---|---|
| 1 CONTRACTOR TO BE DETERMINED | E03 | | | | | $0 | 0% | 0 |
| Watershed Activities in Watersheds Tributary to Lake Merritt and Laguna Creek | | | | | | | | |
| 2 APPLIED MARINE SCIENCES | E03 | | | | | $65,000 | 3% | 9,436 |
| Develop Watershed Study Framework, Assess Pilot Project Activities | | | | | | | | |
| 3 NAME OF CONTRACTOR | | | | | | | | |
| Dexcription of service | | | | | | | | |
| 4 STAFF | | | | | | $56,309 | 2% | 8,174 |
| E. DA COSTA | J03 | 29 | 58.00 | | $1,682 | | | |
| A. FENG | J03 | 399 | 63.00 | | $25,137 | | | |
| J. SCANLIN | J03 | 134 | 80.00 | | $10,720 | | | |
| LABOR OVERHEAD | | | | | $18,770 | | | |
| TOTAL FOCUSED WATERSHED STUDIES | | | | | | $121,309 | 5% | 17,610 |
| HRS. | | 562 | | | | | | |

## 4. WATER QUALITY MONITORING

| Item | Code | Hours | Rate | | Cost | GENERAL PROGRAM AMOUNT | % of Grand Total | Fremont Contribution |
|---|---|---|---|---|---|---|---|---|
| 1 REGIONAL WATER BOARD FEE FOR REGIONAL MONITORING PROGRAM | E04 | | | | | $140,000 | 6% | 20,323 |
| Annual Fee Required by Regional Water Board to Monitor and Report on Health (Water Quality) of San Francisco Bay Estuary | | | | | | | | |
| 2 APPLIED MARINE SCIENCES (AMS) | E04 | | | | | $65,000 | 3% | 9,436 |
| Mercury Testing | | | | | | | | |
| 3 ENVIRONMENTAL IMPACT PLANNING CORP. (EIP) | E04 | | | | | $140,000 | 6% | 20,323 |
| Watershed Inventory, Data Management, and Geographical Information Systems Assistance | | | | | | | | |
| 4 URS CONSULTANTS | E04 | | | | | $130,000 | 6% | 18,871 |
| Assess Fisheries, Contact Recreation, Litter and Leaf Control | | | | | | | | |
| 5 REQUIRED CONTRIBUTION TO WATER QUALITY ATTAINMENT STRATEGIES | E04 | | | | | $160,000 | 7% | 23,226 |
| Contribution to MOU-based Total Maximum Daily Load compliance tasks. | | | | | | | | |
| 6 DIAZINON GRANT | E04 | | | | | $10,000 | 0% | 1,452 |
| Diazinon Grant | | | | | | | | |
| 7 SYSTECH ENGINEERING | | | | | | $46,000 | 2% | 6,678 |
| Analytical Services | | | | | | | | |
| 8 CLEAN WATER AGENCIES TMDL COPPER-NICKEL MONITORING PROJECT | | | | | | $40,000 | 2% | 5,807 |
| Dexcription of service | | | | | | | | |
| 9 NAME OF CONTRACTOR | | | | | | | | |
| Dexcription of service | | | | | | | | |
| 10 STAFF | | | | | | $124,077 | 5% | 18,011 |
| E. DA COSTA | J04 | 20 | 58.00 | | $1,160 | | | |
| A. FENG | J04 | 956 | 63.00 | | $60,228 | | | |
| S. MILLER | J04 | 300 | 43.00 | | $12,900 | | | |
| TRAINEE | J04 | 40 | 26.00 | | $1,040 | | | |
| J. SCANLIN | J04 | 53 | 80.00 | | $4,240 | | | |
| G. SHAWLEY | J04 | 50 | 63.00 | | $3,150 | | | |
| LABOR OVERHEAD | | | | | $41,359 | | | |
| TOTAL WATER QUALITY MONITORING | | | | | | $855,077 | 37% | 124,126 |
| HRS. | | 1,419 | | | | | | |

## 5. PUBLIC INFORMATION/PARTICIPATION

| Item | Code | GENERAL PROGRAM AMOUNT | % of Grand Total | Fremont Contribution |
|---|---|---|---|---|
| 1 TARGETED OUTREACH / REGIONAL ADVERTISING | E05 | $0 | 0% | 0 |
| Targeted Outreach to Meet Public Information Requirements - REGIONAL ADVERTISING | | | | |
| 2 EISENBERG OLIVIERI ASSOCIATES (EOA) | E05 | $45,000 | 2% | 6,532 |
| Evaluate Effectiveness, Clean Water City and County Staff Training, Assist Implementation | | | | |

Table C-5. Continued.

| | Code | Hrs | Rate | Amount | Total | % of Grand Total | Fremont Contribution |
|---|---|---|---|---|---|---|---|
| 3 ESTUARY ACTION CHALLENGE | E05 | | | | $30,000 | 1% | 4,355 |
| Educational Outreach for Organized Activities and Events | | | | | | | |
| 4 AQUATIC OUTREACH INST. (AOI) Kids in Creeks | E05 | | | | $91,500 | 4% | 13,282 |
| Community Stewardship Grants, Educ.Outreach (Kids in Creeks, Gardens, Marshes & Workshops) Assist Implementation | | | | | | | |
| 5 RESOURCE CONSERVATION DIST. (RCD) - Baysavers | E05 | | | | $56,000 | 2% | 8,129 |
| Educational Support - Baysavers Elementary Education Curriculum and Implementation | | | | | | | |
| 6 BAY AREA ENVIRONMENTAL EDUCATION RESOURCE FAIR (BAEER FAIR) | E05 | | | | $2,500 | 0% | 363 |
| Educational Support | | | | | | | |
| 7 CONTRACTOR TO BE DETERM. GEN'L OUTREACH | | | | | $50,000 | 2% | 7,258 |
| Reinforce Message in Communities | | | | | | | |
| 8 STAFF | | | | | $74,925 | 3% | 10,876 |
| L. CERVANTES | J05 | 850 | 53.00 | $45,050 | | | |
| S. GOSSELIN | J05 | 70 | 70.00 | $4,900 | | | |
| LABOR OVERHEAD | | | | $24,975 | | | |
| TOTAL PUBLIC INFORMATION / PARTICIPATION | | | | | $349,925 | 15% | 50,796 |
| HRS. | | 920 | | | | | |

## 6. MUNICIPAL MAINTENANCE PRACTICES

| | Code | Hrs | Rate | Amount | Total | % of Grand Total | Fremont Contribution |
|---|---|---|---|---|---|---|---|
| 1 EISENBERG OLIVIERI ASSOCIATES (EOA) | E06 | | | | $85,000 | 4% | 12,339 |
| Update and Develop Perform. Stds, Coordinate Maint Actvties, ID Struct Controls, Maint. Data Mgmt, Maint. Outreach, Maint Component Mgmt. | | | | | | | |
| 2 STAFF | | | | | $5,760 | 0% | 836 |
| J. SCANLIN | J06 | 48 | 80.00 | $3,840 | | | |
| LABOR OVERHEAD | | | | $1,920 | | | |
| TOTAL MUNICIPAL MAINTENANCE | | | | | $90,760 | 4% | 13,175 |
| HRS. | | 48 | | | | | |

## 7. NEW DEVELOPMENT AND CONSTRUCTION SITE CONTROLS

| | Code | Hrs | Rate | Amount | Total | % of Grand Total | Fremont Contribution |
|---|---|---|---|---|---|---|---|
| 1 EISENBERG OLIVIERI ASSOCIATES (EOA) | E07 | | | | $80,000 | 3% | 11,613 |
| Guidance on Stormwtr Controls, Constr. Actvties, Outreach, Perf. Stds, Wshed Inventry, Coord. w/ District, Component Mgmt. | | | | | | | |
| 2 REPROGRAPHIC SVCS. ALCOLINK (Brochures) | | | | | $15,000 | 1% | 2,177 |
| Description of service | | | | | | | |
| 3 STAFF | | | | | $10,650 | 0% | 1,546 |
| D. BACH | J07 | 100 | 47.00 | $4,700 | | | |
| J. SCANLIN | J07 | 30 | 80.00 | $2,400 | | | |
| LABOR OVERHEAD | | | | $3,550 | | | |
| TOTAL NEW DEVELOPMENT AND CONSTRUCTION SITE CONTROLS | | | | | $105,650 | 5% | 15,337 |
| HRS. | | 130 | | | | | |

## 8. ILLICIT DISCHARGE CONTROLS

| | Code | Hrs | Rate | Amount | Total | % of Grand Total | Fremont Contribution |
|---|---|---|---|---|---|---|---|
| 1 EISENBERG OLIVIERI ASSOCIATES (EOA) | E08 | | | | $35,000 | 1% | 5,081 |
| Assist to Eliminate Non-Stormwater Discharges, Analyze Illicit Discharge Findings, Share Information on Non-Stormwater Discharges, Illicit Discharge Reporting | | | | | | | |
| 2 STAFF | | | | | $5,760 | 0% | 836 |
| J. SCANLIN | J08 | 48 | 80.00 | $3,840 | | | |
| LABOR OVERHEAD | | | | $1,920 | | | |
| TOTAL ILLICIT DISCHARGE CONTROLS | | | | | $40,760 | 2% | 5,917 |
| HRS. | | 48 | | | | | |

## 9. INDUSTRIAL INSPECTION PROGRAM

| | Code | Hrs | Rate | Amount | Total | % of Grand Total | Fremont Contribution |
|---|---|---|---|---|---|---|---|
| 1 EISENBERG OLIVIERI ASSOCIATES (EOA) | E09 | | | | $115,000 | 5% | 16,694 |
| Conduct Insp & Outreach Activtes, Track Findings, Share Info on Facilites, Refine Indus BMP Guidelines, Insp Training, Insp Reporting | | | | | | | |
| 2 STAFF | | | | | $5,340 | 0% | 775 |
| J. SCANLIN | J09 | 45 | 80.00 | $3,560 | | | |
| LABOR OVERHEAD | | | | $1,780 | | | |
| TOTAL INDUSTRIAL INSPECTION PROGRAM | | | | | $120,340 | 5% | 17,469 |
| CLEAN WATER DIV. STAFF HRS. | | 45 | | | | | |
| **TOTAL GENERAL PROGRAM** | | | | | **$2,342,113** | 100% | 339,990 |

MAKE ENTRIES IN YELLOW SHADED CELLS ONLY

| STAFF | HRS | AMOUNT |
|---|---|---|
| D. Bach | 100 | $4,700 |
| L. Cervantes | 850 | $45,050 |
| E. da Costa | 49 | $2,842 |
| A. Feng | 1,355 | $85,365 |
| S. Gosselin | 70 | $4,900 |
| R. Hale | 300 | $25,500 |
| S. Miller | 300 | $12,900 |
| J. Scanlin | 1,690 | $135,160 |
| G. Shawley | 195 | $12,285 |
| Trainee | 40 | $1,040 |
| TOTAL HOURS | 4,949 | |
| TOTAL BURDENED LABOR | | $329,742 |
| TOTAL STAFF with overhead | | $494,613 |

To change revision date, go to tab entitled ALTERNATIVES - STAFFING & COSTS

REVISION: 2/3/02

FUNDING

AVAILABLE FUND BALANCE: $242,113 (for current fiscal year)

| | CONTRIBUTIONS | PROPORTION | |
|---|---|---|---|
| 5083 | $83,580 | 0.03980 | ALAMEDA |
| 5084 | $21,000 | 0.01000 | ALBANY |
| 5085 | $107,310 | 0.05110 | BERKELEY |
| 5086 | $49,350 | 0.02350 | DUBLIN |
| 5087 | $21,000 | 0.01000 | EMERYVILLE |
| 5088 | $339,990 | 0.16190 | FREMONT |
| 5089 | $235,410 | 0.11210 | HAYWARD |
| 5090 | $123,270 | 0.05870 | LIVERMORE |
| 5091 | $57,750 | 0.02750 | NEWARK |
| 5092 | $462,420 | 0.22020 | OAKLAND |
| 5093 | $21,000 | 0.01000 | PIEDMONT |
| 5094 | $114,030 | 0.05430 | PLEASANTON |
| 5096 | $104,160 | 0.04960 | SAN LEANDRO |
| 5097 | $104,790 | 0.04990 | UNION CITY |
| 5082 | $254,940 | 0.12140 | UNINCORPORATED AREA (from F1SW82 spread) |
| TOTAL CONTRIBUTIONS | $2,100,000 | 1.00000 | TOTAL SHARES |
| TOTAL FUNDING | $2,342,113 | | |

PROGRAM DETAILS:

| | |
|---|---|
| STAFF WITH OVERHEAD | $494,613 |
| SPECIALIZED SERVICES | $1,752,500 |
| OTHER EXPENSES (fees, etc.) | $95,000 |
| PROGRAM TOTAL: | $2,342,113 |

| DETAIL: | MULTI-TASK CONSULTANTS |
|---|---|
| EOA TOTAL | $583,000 |
| AMS TOTAL | $130,000 |

(Source: Hale, pers. comm., 7/15/04)

This appendix contains backup calculations for each cost survey category in Section 6 and the sources of the cost data. The Fresno-Clovis Metropolitan Area (FCMA) covers the area served by the Fresno Metropolitan Flood Control District (FMFCD). Stormwater permittees in this area include the County of Fresno, city of Fresno, city of Clovis, and the California State University at Fresno (CSUF). The FMFCD was the lead agency for communication on this project. Figure D-1 illustrates how data is shared throughout the tables.

Table D-1 contains all costs from all copermittees organized into the cost survey categories and the remaining tables provide backup to the numbers in Table D-1. The relationship of these tables is described below and presented in figure D-1. Table D-2 contains FMFCD cost organized by survey category but with added detail than what is provided in Table D-1. The cost figures in Table D-2 were summarized from the FMFCD accounting system cost summary (Table D-7).

Table D-3 summarizes the costs for the city of Clovis, Fresno County, city of Fresno, and CSUF respectively. These costs include budgeted costs and actual street sweeping costs, which are subtotaled for each cost survey category.

Table D-4 presents the allocation of city staff labor cost to the stormwater program. Table D-5 presents street sweeping data while Table D-6 presents a recreated portion of an FMFCD financial statement which was used for comparison to stormwater costs submitted by city staff.

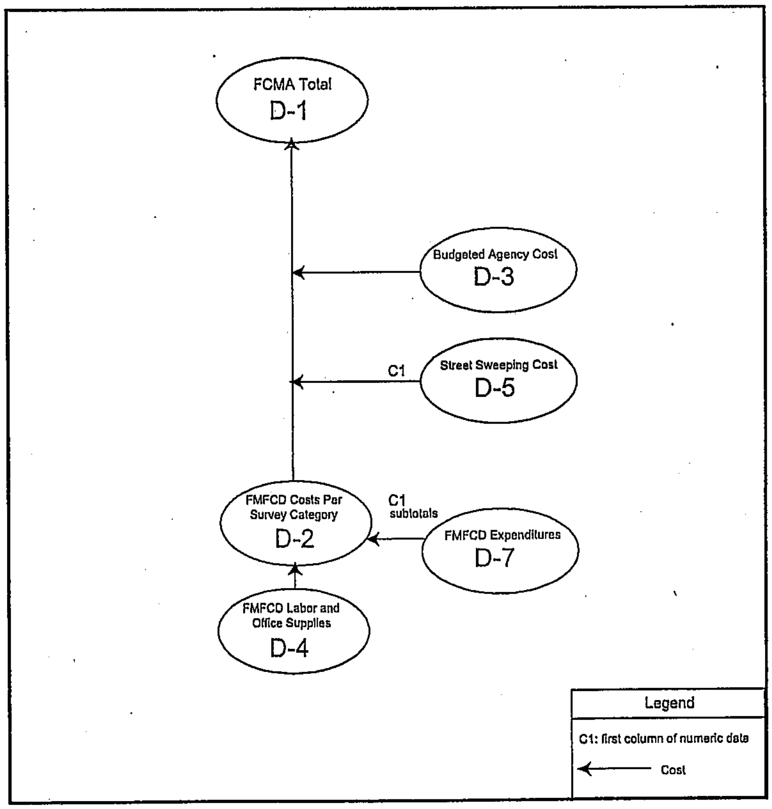




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Figure D-1. Fresno-Clovis Metropolitan Area Flowchart

### *Other Agency Breakdown*

Table D-3 contains the budgeted costs contained in the SWQMP report (FMFCD, 1999). These costs are subtotaled for each cost survey category and the subtotals are brought forward to Table D-1. Except for the FMFCD, which submitted actual costs, the costs were taken from the 00/01 budget for the other agencies as presented in the SWMP published in 1999 (FMFCD, 1999). The 00/01 year was used because the implementation of the program under the new permit was delayed for two years. The SWMP assumed the permit would be adopted in 1999 and the first fiscal year of the new program would be 99/00. The permit was not adopted until 2001 and the first fiscal year implementing the new stormwater permit was 00/01. In 02/03, the program only had one year of development. Thus, the second year costs were taken from the SWMP to represent 02/03 costs on the advice of FMFCD staff. Table D-3 includes a 'baseline' cost element. This is for the staff labor of the programs as they already existed at the start of the new permit (Rourke, pers. comm., 6/25/04). Table D-3 also contains an added line item for actual street sweeping costs pulled forward from Table D-5.

Table D-5 contains the street sweeping data collected for the FCMA. Table D-9 also calculates street sweeping cost per mile and estimated sweeping frequency. It should be noted that the estimated frequency for the city of Clovis is nearly four times a week for all streets. This seemed high and it could not be verified with the city. The cost per mile was relatively low ($13), which indicates the costs may be accurate and only the total miles swept is in question.

### *Notes on Labor Cost*

For the FMFCD, the labor costs of the stormwater staff is not distributed among the various programs. Instead, it is all captured under Overall Stormwater Program Management. However, the labor costs from the other agencies within the FMFCD were able to distribute their labor among various programs. This should be considered when comparing costs to other municipalities where such costs are distributed.

Detailed descriptions of how the costs were developed are contained in the following paragraphs.

The reason we allocate FMFCD cost, but not other overall program costs for other cities is because the services provided by outside agencies (e.g. ACCWP to Fremont) are paid for by Fremont. FMFCD gets funds for stormwater directly from households "user fees", "utility bills". If FMFCD did not provide this "free" service, the cities would have to pay for them.

For agencies other than FMFCD, external contracting was not determined for each cost. It is only presented in the text of this appendix on a case-by-case basis. For FMFCD this information is presented in Table D-2.

### Construction Site Stormwater Runoff Control

The total cost of this category was $81,800. The costs allocated for this category were only from the city of Clovis (Table D-2), county of Fresno (Table D-3), and the city of Fresno (Table D-4). No statistics were available that described the activity except for the city of Clovis. Clovis conducted 713 inspections at a cost of $29,600, which averages to $42 per inspection. The primary activities performed by each agency were plan reviews, site inspections, enforcement, and employee training. Other activities performed were as follows (source: annual stormwater report, FMFCD, 2003b):

- Identified 163 private detention basins and mailed pond maintenance and vector control fact sheets to pond owners
- Conducted 9 stormwater training workshops and safety tailgate sessions for general contractors, construction site superintendents, field inspectors, plan designers, and municipal regulators
- Increased construction sire inspections and follow-up inspection referrals to the District
- Reviewed construction site guidelines
- Sent out an "Action Alert" notifying area construction sites and companies of new Phase II regulations and schedules
- Included new regulations in training courses and site visits
- Modified the SWPPP to include sampling and analysis guidance
- The District conducted 48 inspections at 15 construction sites

### Illicit Discharge Detection and Elimination (IDDE)

The total cost of this category was $13,176. This cost was for investigation, inspection and enforcement. The costs for the FMFCD, county of Fresno, the city of Clovis, and the city of Fresno accounted for two percent, eight percent, eighty-two percent, and eight percent of the IDDE costs, respectively. Activities in this category included the following (source: annual stormwater report, FMFCD, 2003b):

- Field inspectors were trained to identify and report illegal disposals
- Fifty thousand paint sticks were distributed at 17 paint retailers throughout the permit area
- Recharged irrigation waters and nuisance flows
- Participated in Water Awareness Committee and P2 Committee
- Reviewed and revised referral procedures between the District and Copermittees
- Conducted inspector training via workshops and tailgates
- Conducted firefighter training

- The County sponsored the California Conservation Corp to stencil 527 storm drain inlets in Clovis
- Students stenciled 73 storm drain inlets in the city of Clovis
- The District conducted 71 complaint inspections in response to citizen or Copermittee referrals
- The Clovis Fire Department responded to 82 hazardous waste spills
- The District developed and aired water conservation theater advertisement slides at two major movie theaters with over 30 screens and sent out 23,000 utility bill inserts to Clovis households in their monthly water bill
- The city of Clovis sent out notices to 22,360 customers reminding them of the outdoor watering rules and what they can to reduce runoff
- In Fresno County, the emergency response team program documented over 289 units of filed activity involving hazardous waste, which included complaints and follow-up enforcement inspections

### *Industrial and Commercial Management Programs*

The cost for this category was $47,480. FMFCD activities include the purchase of phone complaint forms employee training of the other agencies. Other activities in this category included (source: annual stormwater report, FMFCD, 2003b):

- Held industrial training workshops
- Distributed over 65 model SWPPPs
- Coordinated with County Hazardous Waste and Fresno Industrial Waste inspectors to review inspection and referral procedures
- Conducted audits of 5 Copermittee corporation yards
- The District conducted 14 complaint-driven commercial and industrial inspections and 42 routine industrial inspections at NPDES permitted facilities

### *Overall Stormwater Program Management*

The total cost of this category was $560,495. FMFCD accounted for approximately 98 percent of this category's cost. Most of this was labor cost (see Table D-7 for details). The other costs for this category were attributable to the following activities:

- Travel
- Meetings and conferences
- Dues and fees
- Food
- Printing

- Office supplies
- SWRCB fees
- Handbooks

### *Pollution Prevention and Good Housekeeping for Municipal Operations*

The total cost for this category was $2,240,605. Clovis accounted for 28% and the city of Fresno accounted for 70% due primarily to street sweeping costs (Table D-9).

Other agency costs were for road maintenance, street cleaning, corporation yard guidance, and staff labor.

Other specific activities attributed to this category included (source: annual stormwater report, FMFCD, 2003b):

- Completed digitizing the District's stormwater conveyance system into the District's GIS system
- Developed, organized, and facilitated stormwater pollution prevention training courses for parks and open space maintenance personnel
- The District removed accumulated sediments from their retention basins
- Training of employees

### *Post Construction Stormwater Management in New Development and Redevelopment*

The total cost of this category was $57,539. Most of the cost for this category was for the detention and retention basin operation and maintenance funded by FMFCD. The following detention and retention maintenance activities were performed:

- Cleaned 35 basins
- Rodent control
- Tree care
- Sediment removal and disposal
- Equipment rental
- Vegetation removal and recycling
- Vaccum truck cleaning
- Reviewed monitoring studies
- Completed standards research
- The District incorporated post construction standards in its Code of Requirements
- Soil monitoring

- Fence repair

The other agencies had no cost attributable to this category.

### *Public Education and Outreach and Public Involvement and Participation*

The total cost of this category was $210,716. Most of the $208,016 paid by FMFCD was for professional services, newspaper advertisements, utility bill inserts, and other miscellaneous costs. The other agency costs were for school education, staff labor, and coordination with other programs. Other activities performed were (source: annual stormwater report, FMFCD, 2003b):

- Developed and aired three new Public Service Announcements (English and Spanish) targeting pollution prevention and water awareness
- Completed seven Clean Storm Water Grants to community organizations focused on stormwater education
- Continued implementation of a community wide integrated pest management program
- Conducted numerous presentations to community groups and school programs
- Produced a new brochure
- Participated in the local Pollution Prevention Committee
- Provided training for local inspectors
- The District maintained active membership with WERF, participated with the National Association of Flood and Storm Water Managers Association, provided $10,000 to WERF for stormwater research initiatives, and provided comments to EPA though the Storm Water Quality Task Force
- Participated in 18 community and public education events
- Provided a public education display illustrating ways to manage solid waste to incorporated cities throughout the County
- Conducted tours of the American Avenue Landfill for fourth grade to college level students
- Developed training manuals, theater slides, bus signage, pond maintenance fact sheets, mosquito abatement, control, and home owner fact sheets to promote BMPs and the SWQMP program
- Updated public education and technical assistance outreach materials
- Developed and implemented IPM Point of Purchase program
- Awarded 20 grants totaling $20,000
- Provided teacher workshops

### *Water Quality Monitoring*

The total cost of this category was $252,918. The costs were for the FMFCD for the following activities:

- Monitoring
- Consulting
- Phone usage
- Communications
- WERF subscription

The other agencies had no cost attributable to this category.

### *References*

FMFCD. 2003. "Annual Report FY 2002-2003, Fresno-Clovis Storm Water Quality Management Program" Volume 1: Program Evaluations.

**Table D-1. Fresno-Clovis Metropolitan Area Costs Organized by Cost Survey Category**

**Cost Survey Categories**
*Activity Description*

**Construction Site Stormwater Runoff Control**

| Description | Relation to Permit[a] | Dollar Amount | Source | % of Category |
|---|---|---|---|---|
| FMFCD | | 0 | N/A | 0.0% |
| City of Clovis | New | 29,600 | Table D-3 | 36.2% |
| County of Fresno | New | 6,900 | Table D-3 | 8.4% |
| City of Fresno | New | 45,300 | Table D-3 | 55.4% |
| CSUF | | 0 | N/A | 0.0% |
| Total | | 81,800 | | 2.4% * |

**Illicit Discharge Detection and Elimination**

| Description | Relation to Permit | Dollar Amount | Source | % of Category |
|---|---|---|---|---|
| *FMFCD* | New | 76 | Table D-2 | 0.6% |
| *City of Clovis* | New | 10,100 | Table D-3 | 76.7% |
| *County of Fresno* | New | 1,000 | Table D-3 | 7.6% |
| *City of Fresno* | New | 1,000 | Table D-3 | 7.6% |
| *CSUF* | New | 1,000 | Table D-3 | 7.6% |
| Total | | 13,176 | | 0.4% * |

**Industrial and Commercial Management Programs**

| Description | Relation to Permit | Dollar Amount | Source | % of Category |
|---|---|---|---|---|
| FMFCD | New | 22,180 | Table D-2 | 46.4% |
| City of Clovis | New | 6,100 | Table D-3 | 12.8% |
| County of Fresno | New | 8,200 | Table D-3 | 17.2% |
| City of Fresno | New | 10,400 | Table D-3 | 21.8% |
| CSUF | New | 900 | Table D-3 | 1.9% |
| Total | | 47,780 | | 1.4% * |

**Overall Stormwater Program Management**

| Description | Relation to Permit | Dollar Amount | Source | % of Category |
|---|---|---|---|---|
| FMFCD | New | 560,895 | Table D-2 | 98.3% |
| City of Clovis | New | 1,600 | Table D-3 | 0.3% |
| County of Fresno | New | 3,200 | Table D-3 | 0.6% |
| City of Fresno | New | 3,200 | Table D-3 | 0.6% |
| CSUF | New | 1,600 | Table D-3 | 0.3% |
| Total | | 570,495 | | 16.4% * |

Table D-1. Continued.

**Pollution Prevention and Good Housekeeping for Municipal Operations**

| Description | Relation to Permit | Dollar Amount | Source | % of Category |
|---|---|---|---|---|
| *FMFCD* | New | 29,409 | Table D-2 | 1.3% |
| *City of Clovis* | Enhanced | 631,696 | Table D-3 | 28.2% |
| *County of Fresno* | Enhanced | 5,300 | Table D-3 | 0.2% |
| *City of Fresno* | Enhanced | 1,572,500 | Table D-3 | 70.2% |
| *CSUF* | Enhanced | 1,700 | Table D-3 | 0.1% |
| Total | | 2,240,605 | | 64.5% * |

**Post Construction Stormwater Management in New Development and Redevelopment**

| Description | Relation to Permit | Dollar Amount | Source | % of Category |
|---|---|---|---|---|
| *FMFCD* | Existing | 57,539 | Table D-2 | 100.0% |
| *City of Clovis* | | 0 | N/A | 0.0% |
| *County of Fresno* | | 0 | N/A | 0.0% |
| *City of Fresno* | | 0 | N/A | 0.0% |
| *CSUF* | | 0 | N/A | 0.0% |
| Total | | 57,539 | | 1.7% * |

**Public Education, Outreach, Involvement, and Participation**

| Description | Relation to Permit | Dollar Amount | Source | % of Category |
|---|---|---|---|---|
| *FMFCD* | New | 208,016 | Table D-2 | 98.7% |
| *City of Clovis* | New | 200 | Table D-3 | 0.1% |
| *County of Fresno* | New | 2,500 | Table D-3 | 1.2% |
| *City of Fresno* | | 0 | N/A | 0.0% |
| *CSUF* | | 0 | N/A | 0.0% |
| Total | | 210,716 | | 6.1% * |

**Water Quality Monitoring**

| Description | Relation to Permit | Dollar Amount | Source | % of Category |
|---|---|---|---|---|
| *FMFCD* | New | 252,918 | Table D-2 | 100.0% |
| *City of Clovis* | | 0 | N/A | 0.0% |
| *County of Fresno* | | 0 | N/A | 0.0% |
| *City of Fresno* | | 0 | N/A | 0.0% |
| *CSUF* | | 0 | N/A | 0.0% |
| Total | | 252,918 | | 7.3% * |

**Total Stormwater Cost** **3,475,029**

a. This column indicates whether required activities were being performed prior to stormwater permits. In some cases activities were enhanced due to permit requirements.

* This percentage is calculated by dividing the total "cost survey category" cost by the "total stormwater cost".

Table D-2. **FMFCD Costs Organized by Cost Survey Category**

Cost Survey Categories

*Activity Description*

**Construction Site Stormwater Runoff Control**

| Description | External Contract | Relation to Permit[a] | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 0 | | | | | | | |
| Total | | | 0 | | | of total FMFCD stormwater program costs | | | | |

**Illicit Discharge Detection and Elimination**

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Investigation, Inspection, Enforcement* | | New | 76 | Table D-7, Item 39 | 100% | | | | | |
| Total | | | 76 | | 0.0% | of total FMFCD stormwater program costs | | | | |

**Industrial and Commercial Management Programs**

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Phone complaints* | | New | 333 | Table D-7, Item 58 | 1.5% | | | | | |
| *Geosyntec services* | x | New | 21,791 | Table D-7, Items 15 & 16 | 98.2% | | | | | |
| *Miscellaneous* | | New | 56 | Table D-7, Item 17 | 0.3% | | | | | |
| Total | | | 22,180 | | 2.0% | of total FMFCD stormwater program costs | | | | |

Table D-1 continued

**Overall Stormwater Program Management**

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Travel* | | New | 2,382 | Table D-7, Items 10 & 50 | 0.4% | | | | | |
| *Meetings and conferences* | | New | 1,508 | Table D-7, Items 11& 51 | 0.3% | | | | | |
| *Dues and fees* | | New | 10,000 | Table D-7, Item 12 | 1.8% | | | | | |
| *Training* | | New | 1,261 | Table D-7, Items 13 & 53 | 0.2% | | | | | |
| *Miscellaneous expenses* | | New | 7,519 | Table D-7, Items 14 & 56 | 1.3% | | | | | |
| *Food* | | New | 341 | Table D-7, Item 45 | 0.1% | | | | | |
| *Printing* | | New | 622 | Table D-7, Item 47 | 0.1% | | | | | |
| *Office supplies* | | New | 172 | Table D-7, Item 48 | 0.0% | | | | | |
| *SWRCB fees* | | New | 17,750 | Table D-7, Item 49 | 3.2% | | | | | |
| *Handbooks* | | New | 66 | Table D-7, Item 54 | 0.0% | | | | | |
| *Program expenses* | | New | 112 | Table D-7, Item 57 | 0.0% | | | | | |
| *Personnel expenses* | | New | 498,300 | Table D-4 | 88.8% | | | | | |
| *Office administration* | | New | 20,864 | Table D-4 | 3.7% | | | | | |
| Total | | | 560,895 | | 49.6% | of total FMFCD stormwater program costs | | | | |

Table D-2. Continued.

**Pollution Prevention and Good Housekeeping for Municipal Operations**

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *BMP Hanbook Update* | | New | 10,000 | Table D-7, Item 2 | 34.0% | | | | | |
| *Geosyntec services* | x | New | 1,996 | Table D-7, Item 3 | 6.8% | | | | | |
| *Truck cleaning* | | New | 15,749 | Table D-7, Items 33 & 35 | 53.6% | | | | | |
| *Utility expense* | | New | 1,007 | Table D-7, Item 36 | 3.4% | | | | | |
| *Fresno Pipeline* | | New | 657 | Table D-7, Item 34 | 2.2% | | | | | |
| Total | | | 29,409 | | 2.6% | of total FMFCD stormwater program costs | | | | |

Table D-7 continued

**Post Construction Stormwater Management in New Development and Redevelopment**

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Basin maintenance* | | Existing | 8,174 | Table D-7, Item 19 | 14.2% | 8 | basins | FMFCD, 2003b | 7,192.34 | category $/basin |
| *Wild agreement* | x | Existing | 2,460 | Table D-7, Item 20 | 4.3% | | | | | |
| *Rodent control* | | Existing | 1,380 | Table D-7, Item 21 | 2.4% | | | | | |
| *Tree care* | | Existing | 290 | Table D-7, Item 22 | 0.5% | | | | | |
| *Spruce Ave* | | Existing | 3,439 | Table D-7, Item 23 | 6.0% | | | | | |
| *Miscellaneous expenses* | | Existing | 2,237 | Table D-7, Item 24 | 3.9% | | | | | |
| *Fuel expense* | | Existing | 1,230 | Table D-7, Item 25 | 2.1% | | | | | |
| *Matt and sons agreement* | x | Existing | 16,989 | Table D-7, Item 26 | 29.5% | | | | | |
| *Equipment rental* | | Existing | 433 | Table D-7, Item 27 | 0.8% | | | | | |
| *Greenwaste* | | Existing | 2,365 | Table D-7, Item 28 | 4.1% | | | | | |
| *Vaccum truck cleaning* | | Existing | 1,015 | Table D-7, Item 29 | 1.8% | | | | | |
| *Matt and sons* | x | Existing | 2,129 | Table D-7, Item 30 | 3.7% | | | | | |
| *Cerutti agreement* | x | Existing | 1,825 | Table D-7, Item 31 | 3.2% | | | | | |
| *Emmetts agreement* | x | Existing | 2,560 | Table D-7, Item 32 | 4.4% | | | | | |
| *Fence repair* | | Existing | 584 | Table D-7, Item 37 | 1.0% | | | | | |
| *Soil monitoring* | | Existing | 10,428 | Table D-7, Item 38 | 18.1% | | | | | |
| Total | | | 57,539 | | 5.1% | of total FMFCD stormwater program costs | | | | |

Table D-2. Continued.

**Public Education, Outreach, Involvement, and Participation**

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Panagraph Inc.* | x | New | 47,008 | Table D-7, Item 7 | 22.6% | | | | | |
| *Panagraph services* | x | New | 39,177 | Table D-7, Item 8 | 18.8% | | | | | |
| *Miscellaneous expenses* | | New | 96,690 | Table D-7, Items 9, 18, & 46 | 46.5% | | | | | |
| *Utility bill inserts* | | New | 2,525 | Table D-7, Item 55 | 1.2% | | | | | |
| *Newspaper description* | | New | 15,095 | Table D-7, Item 59 | 7.3% | | | | | |
| *Grant* | | New | 7,521 | Table D-7, Item 52 | 3.6% | | | | | |
| Total | | | 208,016 | | 18.4% | of total stormwater cost | | | | |

Table D-1 continued

**Water Quality Monitoring**

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Geosyntec monitoring* | x | New | 44,334 | Table D-7, Item 1 | 17.5% | | | | | |
| *Sheit, Handon and Hall* | x | New | 298 | Table D-7, Item 4 | 0.1% | | | | | |
| *LWA monitoring* | x | New | 156,663 | Table D-7, Items 5 & 40 | 61.9% | | | | | |
| *LWA services* | x | New | 40,258 | Table D-7, Items 6 & 43 | 15.9% | | | | | |
| *Phone expense* | | New | 282 | Table D-7, Item 41 | 0.1% | | | | | |
| *Communication expense* | | New | 1,083 | Table D-7, Item 42 | 0.4% | | | | | |
| *WERF* | | New | 10,000 | Table D-7, Item 44 | 4.0% | | | | | |
| Total | | | 252,918 | | 22.4% | of total FMFCD stormwater program costs | | | | |

**Total FMFCD Stormwater Cost** **1,131,033**

a. This column indicates whether required activities were being performed prior to stormwater permits. In some cases activities were enhanced due to permit requirements.

Table D-3. Summary of Budgeted Stormwater Costs for Fresno Agencies

| Item # | Program | Description | City of Clovis | County of Fresno | City of Fresno | CSUF |
|---|---|---|---|---|---|---|
| | Public Involvement and Education | Coordinate with other programs | 0 | 400 | 0 | 0 |
| | Public Involvement and Education | Maintain and promote school education | 200 | 0 | 0 | 0 |
| | Public Involvement and Education | Baseline costs | 0 | 2,100 | 0 | 0 |
| 1 | **Subtotal** | | **200** | **2,500** | **0** | **0** |
| | Illicit Discharge | Implement inspector training | 3,200 | 0 | 0 | 0 |
| | Illicit Discharge | Train response personnel | 3,200 | 0 | 0 | 0 |
| | Illicit Discharge | Baseline costs | 3,700 | 1,000 | 1,000 | 1,000 |
| 2 | **Subtotal** | | **10,100** | **1,000** | **1,000** | **1,000** |
| | Operations and Maintenance | Implement guidance for road maintenance activities | 700 | 0 | 0 | 0 |
| | Operations and Maintenance | Implement street cleaning practices (see 'Actual' costs) | 100 | 0 | 0 | 0 |
| | Operations and Maintenance | Implement corporation yard operation guidance | 2,500 | 0 | 0 | 0 |
| | Operations and Maintenance | Baseline costs | 3,300 | 5,300 | 4,300 | 1,700 |
| | Operations and Maintenance | *Actual street sweeping cost* | 625,096 | 0 | 1,568,200 | 0 |
| 3 | **Subtotal** | | **631,696** | **5,300** | **1,572,500** | **1,700** |
| | Construction and Development | Review plans, inspect sites, enforce control requirement | 19,100 | 2,600 | 13,700 | 0 |
| | Construction and Development | Train agency personnel and development community | 100 | 1,100 | 10,500 | 0 |
| | Construction and Development | Baseline costs | 10,100 | 3,200 | 19,000 | 0 |
| | Construction and Development | Consider standard requirements | 300 | 0 | 0 | 0 |
| | Construction and Development | Implement construction site guidelines | 0 | 0 | 2,100 | 0 |
| 4 | **Subtotal** | | **29,600** | **6,900** | **45,300** | **0** |
| | Commercial and Industrial | Implement inspection and enforcement procedures | 0 | 100 | 0 | 0 |
| | Commercial and Industrial | Train employees | 1,600 | 100 | 0 | 0 |
| | Commercial and Industrial | Baseline costs | 4,500 | 8,000 | 10,400 | 900 |
| 5 | **Subtotal** | | **6,100** | **8,200** | **10,400** | **900** |
| 6 | ***Overall Stormwater Program Man.*** [1] | Administration and management | **1,600** | **3,200** | **3,200** | **1,600** |
| | Total | | **679,296** | **27,100** | **1,632,400** | **5,200** |

Source: Fresno-Clovis Storm Water Quality Management Program, 00/01 budget (Fresno, 1999)

1. The program title was assigned and did not come from the reference.

**Table D-4. Calculation of Labor and Office Supply Costs for Stormwater**

| CAFR Description | Amount | Allocation to Stormwater | Reference | Stormwater Cost |
|---|---|---|---|---|
| Personnel expense[1] | $4,529,998 | 11% | Palmoville, pers. comm., 6/10/04 | $ 498,299.78 |
| Office Administration[1] | $189,671 | 11% | Palmoville, pers. comm., 6/10/04 | $ 20,863.81 |

*1. From page 20 of FMFCD CAFR, Statement of Revenues, Expenditures and Changes in Fund Balance - Government Funds and Reconcilliation to the Statement of Activities*

**Table D-5. Street Sweeping Data Submitted by City Staff and Normalization**

| Entity | Cost[1] | Curb Miles Swept[2] | Cost Per Mile Swept | Approximate City Street Miles |
|---|---|---|---|---|
| City of Fresno | 1,568,200 | 94,495 | 16.60 | |
| City of Clovis | 625,096 | 47,430 | 13.18 | 235 |
| CSUF | N/A | 465 | N/A | |
| County of Fresno | N/A | 21 | N/A | |
| Total | 2,193,296 | 142,411 | 15.40 | |

1. (Source: Rourke, pers. comm., 8/02/04)
2. (Source: FMFCD, 2003b)

**Table D-6. Recreated Portion of FMFCD Financial Statement**

**Fresno Metropolitan Flood Control District**
**Statement of Activities**
**for the year ended June 30, 2003**

| Functions/Programs | Expenses |
|---|---|
| General government | $6,388,084 |
| Flood control system | 4,010,377 |
| Storm water quality | 611,870 |
| Interest on long-term debt | 1,010,490 |
| Total | 12,020,821 |

(Source: FMFCD, 2003a.)

**Table D-7. Source Data Table Submitted by FMFCD (cost survey categories added)**

| FMFCD Category | Item Number | DESC | APDesc | GL_Amt | Cost Survey Category[1] |
|---|---|---|---|---|---|
| **Municipal NPDES Program Development 7030-7036** | | | | | |
| | | **Consulting Services** | | | |
| | 1 | GeoSyntec Consultants | 2001-2002 SWQM | 4,575.17 | Monitoring |
| | 1 | GeoSyntec Consultants | 2001-2002 Stormwater Quality M | 952.22 | Monitoring |
| | 2 | San Bernardino County | Updated Best Mgmt Practice Han | 10,000.00 | Pollution Prevention |
| | 3 | GeoSyntec Consultants | Service through 12/03/2002 | 683.78 | Pollution Prevention |
| | 3 | GeoSyntec Consultants Inc | Service thru 01/07/2003 | 230.94 | Pollution Prevention |
| | 1 | GeoSyntec Consultants Inc | 03/2003 SWQ Monitoring | 7,029.84 | Monitoring |
| | 1 | GeoSyntec Consultants Inc | 03/2003 SWQ Monitoring | 2,343.45 | Monitoring |
| | 3 | GeoSyntec Consultants Inc | 05/2002 Communication Fee | 0.30 | Pollution Prevention |
| | 1 | GeoSyntec Consultants Inc | 4/2003 Storm Water Monitoring | 8,262.75 | Monitoring |
| | 1 | GeoSyntec Consultants Inc | 02-03 Storm Water Monitoring | 7,302.26 | Monitoring |
| | 1 | GeoSyntec Consultants Inc | 02-03 Stormwater Quality Monit | 4,867.72 | Monitoring |
| | 3 | GeoSyntec Consultants Inc | Service thru 06/30/03 | 1,081.33 | Pollution Prevention |
| | 1 | GeoSyntec Consultants Inc | 02-03 Stormwater Monitoring | 9,000.47 | Monitoring |
| | Item Number | | **Total Consulting Services** | 56,330.23 | |
| Subtotals | 1 | | GeoSWQM7031 | 44,333.88 | Monitoring |
| | 2 | | SanBMPHan7031 | 10,000.00 | Pollution Prevention |
| | 3 | | GeoService7031 | 1,996.35 | Pollution Prevention |
| | | | Total | 56,330.23 | |
| | | | Difference | 0.00 | |
| | | **Monitoring** | | | |
| | 4 | Scheidt Haydon & Hall | SWQM BM02-01 6/26/02-7/02/02 W | 298.06 | Monitoring |
| | 5 | Larry Walker Associates Inc | Storm Water Quality Monitoring | 3,530.00 | Monitoring |
| | 5 | Larry Walker Associates Inc | 2001-2002 Stormwater Monitorin | 1,680.00 | Monitoring |
| | 5 | Larry Walker Associates Inc | 2001-2002 Stormwater Monitorin | 1,680.00 | Monitoring |
| | 6 | Larry Walker Associates Inc | 09/01/02-09/18/02 Professional | 173.25 | Monitoring |
| | 5 | Larry Walker Associates Inc | 2002-2003 SWQ Monitoring | 132.00 | Monitoring |
| | 5 | Larry Walker Associates Inc | 02-03 Stormwater Quality Monit | 2,262.50 | Monitoring |
| | 5 | Larry Walker Associates Inc | 02-03 Stormwater Monitoring | 3,515.00 | Monitoring |
| | Item Number | | **Total Monitoring** | 13,270.81 | |
| Subtotals | 4 | | SHHSWQM7033 | 298.06 | Monitoring |
| | 5 | | LWASWQM7033 | 12,799.50 | Monitoring |
| | 6 | | LWAProf7033 | 173.25 | Monitoring |
| | | | Total | 13,270.81 | |
| | | | Difference | 0.00 | |
| | | **Public Information** | | | |
| | 9 | Bank of America | Horizon | 25.28 | Public Education |
| | 7 | Panagraph Inc | 07/2002 SWQMP Public Informati | 3,831.50 | Public Education |
| | 9 | Reed & Graham Inc | Bags of Gravel | 42.83 | Public Education |
| | 7 | Panagraph Inc | 2002-2003 SWQMP Public Info & | 1,636.25 | Public Education |
| | 7 | Panagraph Inc | 2001-2002 SWQMP Public Info & | 8,227.38 | Public Education |
| | 7 | Panagraph Inc | 2002-2003 SWQMP Education | 5,100.00 | Public Education |
| | 7 | Panagraph Inc | 2001-2002 SWQMP Education | 1,713.50 | Public Education |
| | 7 | Panagraph Inc | 10/2002 SWQMP Public Info | 4,250.00 | Public Education |
| | 9 | Bank of America | Water Education Foundation | 218.43 | Public Education |
| | 8 | Panagraph Inc | Service through 10/31/2002 | 2,677.50 | Public Education |
| | 8 | Panagraph Inc | Service thru 01/2003 | 3,271.54 | Public Education |
| | 8 | Panagraph Inc | Services thru 12/2002 | 4,160.33 | Public Education |
| | 7 | Panagraph Inc | 2002-2003 SWQMP | 5,876.97 | Public Education |
| | 8 | Panagraph Inc | Services thru 03/2003 | 9,220.35 | Public Education |
| | 7 | Panagraph Inc | SWQMP Public Info & Education | 16,372.78 | Public Education |
| | 8 | Panagraph Inc | 02-03 Public Info & Education | 15,036.32 | Public Education |
| | 8 | Panagraph Inc | 06/2003 Services SWQMP Info | 4,810.73 | Public Education |
| | Item Number | | **Total Public Information** | 86,471.69 | |
| Subtotals | 7 | | PanSWQMP7034 | 47,008.38 | Public Education |
| | 8 | | PanServices7034 | 39,176.77 | Public Education |
| | 9 | | Misc7034 | 286.54 | Public Education |
| | | | Total | 86,471.69 | |
| | | | Difference | 0.00 | |

**Table D-7. Continued.**

| | Item Number | | | | |
|---|---|---|---|---|---|
| | | **General Expenses** | | | |
| | 10 | Bank of America | Hyatt Regency | 180.00 | Management |
| | 10 | Bank of America | Hertz | 93.13 | Management |
| | 10 | Bank of America | City of Fresno Airport | 6.00 | Management |
| | 10 | David J Pomaville | Travel Reimbursement | 5.32 | Management |
| | 10 | Bank of America | Host Airport Hotel | 124.75 | Management |
| | 10 | Bank of America | Hertz | 155.50 | Management |
| | 10 | Bank of America | City of Fresno Parking | 12.00 | Management |
| | 10 | David J Pomaville | Travel Reimbursement | 4.00 | Management |
| | 10 | Doug Harrison | Travel Reimbursement | 32.79 | Management |
| | 10 | Doug Harrison | Travel Reimbursement | 40.00 | Management |
| | 10 | IMPAC Government Services | Radisson Hotel Sacramento | 58.96 | Management |
| | 14 | IMPAC Government Services | Maguire's Chevron | 4.75 | Management |
| | 10 | IMPAC Government Services | Hertz | 81.30 | Management |
| | 14 | IMPAC Government Services | Flag City | 9.55 | Management |
| | 11 | Calif Stormwater Quality Tas | SWQTF September Meeting Fee | 40.00 | Management |
| | 10 | Bank of America | Doubletree Hotel | 108.31 | Management |
| | 10 | Bank of America | City of Fresno Airport Parking | 16.00 | Management |
| | 10 | Bank of America | The Broiler Restaurant | 31.37 | Management |
| | 10 | Bank of America | Hertz Rent A Car | 75.60 | Management |
| | 10 | David J Pomaville | Reimbursement for Parking | 7.00 | Management |
| | 11 | Groundwater Resources Assoc | Nitrate in Groundwater Conf Re | 150.00 | Management |
| | 12 | SWQTF | 2002/2003 Annual Dues | 10,000.00 | Management |
| | 11 | Beck & Duke Travel Service | SWQTF Conference-Ontario | 526.00 | Management |
| | 10 | Bank of America | Holiday Inn on the Bay | 109.40 | Management |
| | 10 | Bank of America | Hertz Rent a Car | 63.00 | Management |
| | 11 | California Storm Water Quali | CASQA Annual Board Meeting | 40.00 | Management |
| | 10 | Bank of America | Oakland Intl Airport Parking | 12.00 | Management |
| | 10 | Bank of America | City of Fresno Airport Parking | 8.00 | Management |
| | 10 | Bank of America | Hertz Rental Car | 87.02 | Management |
| | 11 | Beck & Duke Travel Service | Storm Water Quality Conf San D | 374.00 | Management |
| | 10 | David J Pomaville | Reimbursement Circle K Fuel | 12.33 | Management |
| | 10 | Bank of America | Anthony's Fish Grotto-San Dieg | 22.88 | Management |
| | 10 | Bank of America | Holiday Inn on the Bay | 244.88 | Management |
| | 10 | David J Pomaville | Meal Reimb-Cafe Care Ole' | 5.00 | Management |
| | 10 | David J Pomaville | Meal Reimbursement | 15.00 | Management |
| | 10 | David J Pomaville | Orange Cab-San Diego | 12.00 | Management |
| | 10 | Bank of America | Holiday Inn on the Bay | -109.40 | Management |
| | 13 | Calif Storm Water Quality As | CASQA BMP Training | 480.00 | Management |
| | 10 | Bank of America | Hertz Rent a Car | -63.00 | Management |
| | 13 | Calif Storm Water Quality As | CASWA CA BMP Training | 480.00 | Management |
| | 11 | Bank of America | CASQA & APWA Mtgs-Oakland Intl | 25.00 | Management |
| | 11 | Bank of America | CASQA & APWA Mtgs-Union 76 | 10.82 | Management |
| | 11 | Bank of America | CASQA & APWA Mtgs-Hertz | 152.55 | Management |
| | 11 | Bank of America | CASQA & APWA Mtgs-City of Fres | 16.00 | Management |
| | 11 | David J Pomaville | CASQA Meeting | 62.00 | Management |
| | 10 | Bank of America | CASQA - Hyatt Regency | 155.72 | Management |
| | 10 | Bank of America | CASQA Meeting-Fresno Parking | 16.00 | Management |
| | 10 | Bank of America | CASQA - Hertz | 152.19 | Management |
| | 10 | Bank of America | CASQA - City of Sacto Parking | 5.25 | Management |
| | | | **Total General Expenses** | **14,150.97** | |
| Subtotals | 10 | | Travel7035 | 1,780.30 | Management |
| | 11 | | Meetings/Conferences7035 | 1,396.37 | Management |
| | 12 | | Dues/Fees7035 | 10,000.00 | Management |
| | 13 | | Training7035 | 960.00 | Management |
| | 14 | | Misc7035 | 14.30 | Management |
| | | | Total | 14,150.97 | |
| | | | Difference | 0.00 | |

**Table D-7. Continued.**

Industrial NPDES Prog Development 7040-7046

| | | | | |
|---|---|---|---|---|
| | Consulting Services | | | |
| | 15 GeoSyntec Consultants | 2001-2002 Stormwater Monitorin | 518.75 | Industrial |
| | 15 GeoSyntec Consultants | 2001-2002 SWQM | 20.75 | Industrial |
| | 15 GeoSyntec Consultants | 2001-2002 SWQ Monitoring | 2,488.20 | Industrial |
| | 16 GeoSyntec Consultants | Service through 12/03/2002 | 2,842.11 | Industrial |
| | 15 GeoSyntec Consultants Inc | 03/2003 SWQ Monitoring | 1,258.50 | Industrial |
| | 17 GeoSyntec Consultants Inc | 05/2002 Communication Fee | 56.16 | Industrial |
| | 15 GeoSyntec Consultants Inc | 4/2003 Storm Water Monitoring | 8,106.58 | Industrial |
| | 15 GeoSyntec Consultants Inc | 02-03 Storm Water Monitoring | 1,320.00 | Industrial |
| | 16 GeoSyntec Consultants Inc | Service thru 06/30/03 | 3,465.00 | Industrial |
| | 15 GeoSyntec Consultants Inc | 02-03 Stormwater Monitoring | 1,771.00 | Industrial |
| | Item Number | **Total Consulting Services** | **21,847.05** | |
| Subtotal | 15 | GeoSWQM7041 | 15,483.78 | Industrial |
| | 16 | GeoService7041 | 6,307.11 | Industrial |
| | 17 | Misc7041 | 56.16 | Industrial |
| | | Total | 21,847.05 | |
| | | Difference | 0.00 | |
| Public Information | | | | |
| | 18 Bank of America | Albertson-PIE Meeting | 26.16 | Public Education |

SWQM Operations & Maintenance 7050-7057

| | | | |
|---|---|---|---|
| SWQM Detention Basin Operations and Maintenance | | | |
| 20 Wildlife Control Technology | Agreement #2002-04 | 60.00 | Post Construction |
| 20 Wildlife Control Technology | Agreement #2002-04 | 60.00 | Post Construction |
| 20 Wildlife Control Technology | Agreement #2002-04 | 60.00 | Post Construction |
| 20 Wildlife Control Technology | Agreement #2002-04 | 60.00 | Post Construction |
| 20 Wildlife Control Technology | Agreement #2002-04 | 60.00 | Post Construction |
| 20 Wildlife Control Technology | Agreement #2002-04 | 60.00 | Post Construction |
| 20 Wildlife Control Technology | Agreement #2002-04 | 60.00 | Post Construction |
| 24 R/C Mow-N-Edge Corporation | | 136.51 | Post Construction |
| 20 Wildlife Control Technology | Agreement #2002-04 | 60.00 | Post Construction |
| 24 Mow-N-Edge Corporation | Dev Unit II | 136.51 | Post Construction |
| 21 Wildlife Control Technology | 2003 Rodent Control Srvc | 60.00 | Post Construction |
| 24 Pacific Gas & Electric Compa | Line Extension Deficiency | 403.86 | Post Construction |
| 19 Mow-N-Edge Corporation | 2003 Developed Basin Maint Uni | 136.51 | Post Construction |
| 21 Wildlife Control Technology | 4/2003 Rodent Control | 60.00 | Post Construction |
| 24 Cobb's Tree Care | Agreement 2003-12 | 320.00 | Post Construction |
| 19 Mow-N-Edge Corporation | 2003 Developed Basin Maint Uni | 136.51 | Post Construction |
| 21 Wildlife Control Technology | 5/2003 Rodent Control | 60.00 | Post Construction |
| 19 Mow-N-Edge Corporation | 6/03 Dev Basin Maint-Unit 2 | 136.51 | Post Construction |
| 19 Mow-N-Edge Corporation | 6/03 Dev Basin Maint-Unit 2 | -150.00 | Post Construction |
| 21 Wildlife Control Technology | 6/2003 Rodent Control | 60.00 | Post Construction |
| 20 Wildlife Control Technology | Agreement #2002-04 | 60.00 | Post Construction |
| 20 Wildlife Control Technology | Agreement #2002-04 | 60.00 | Post Construction |
| 21 Wildlife Control Technology | 2003 Rodent Control Srvc | 60.00 | Post Construction |
| 21 Wildlife Control Technology | 4/2003 Rodent Control | 40.00 | Post Construction |
| 21 Wildlife Control Technology | 5/2003 Rodent Control | 40.00 | Post Construction |
| 21 Wildlife Control Technology | 6/2003 Rodent Control | 40.00 | Post Construction |
| 19 Lucas Weed Control, LLC | 07/2002 Undeveloped Basin Main | 106.37 | Post Construction |
| 19 Lucas Weed Control, LLC | 08/2002 Undeveloped Basin Main | 106.37 | Post Construction |
| 20 Wildlife Control Technology | Agreement #2002-04 | 60.00 | Post Construction |
| 20 Wildlife Control Technology | Agreement #2002-04 | 60.00 | Post Construction |
| 19 Lucas Weed Control, LLC | 09/2002 Undeveloped Basin Main | 106.37 | Post Construction |
| 20 Wildlife Control Technology | Agreement #2002-04 | 60.00 | Post Construction |
| 19 Lucas Weed Control, LLC | 10/2002 Undeveloped Basin Main | 106.37 | Post Construction |
| 19 Lucas Weed Control, LLC | 11/2002 Undeveloped Basin Main | 106.37 | Post Construction |
| 20 Wildlife Control Technology | Agreement #2002-04 | 60.00 | Post Construction |
| 19 Lucas Weed Control, LLC | 12/2002 Undeveloped Basin Main | 106.37 | Post Construction |

**Table D-7. Continued.**

| | | | |
|---|---|---|---|
| 20 | Wildlife Control Technology | Agreement #2002-04 | 60.00 Post Construction |
| 19 | Irly-Bird Landscape Company | 01/2003 Undev Basin Maint | 82.89 Post Construction |
| 20 | Wildlife Control Technology | Agreement #2002-04 | 60.00 Post Construction |
| 19 | Irly-Bird Landscape Company | 2003 Undev Basin Maint Unit II | 82.89 Post Construction |
| 20 | Wildlife Control Technology | Agreement #2002-04 | 60.00 Post Construction |
| 21 | Wildlife Control Technology | 2003 Rodent Control Srvc | 60.00 Post Construction |
| 19 | Irly-Bird Landscape Company | 3/03 Undev Basin Maint Unit II | 82.89 Post Construction |
| 21 | Wildlife Control Technology | 4/2003 Rodent Control | 60.00 Post Construction |
| 19 | Irly-Bird Landscape Company | 4/03 Undev Basin Maint Unit II | 82.89 Post Construction |
| 21 | Wildlife Control Technology | 5/2003 Rodent Control | 60.00 Post Construction |
| 21 | Wildlife Control Technology | 6/2003 Rodent Control | 60.00 Post Construction |
| 22 | Cobb's Tree Care | Agreement #2002-12 | 290.00 Post Construction |
| 20 | Wildlife Control Technology | Agreement #2002-04 | 60.00 Post Construction |
| 24 | Mow-N-Edge Corporation | 2002 SWQM Detention Basin O & | 562.49 Post Construction |
| 19 | Lucas Weed Control, LLC | 07/02 Undev Basin Maint-Extra | 80.00 Post Construction |
| 20 | Wildlife Control Technology | Agreement #2002-04 | 60.00 Post Construction |
| 23 | City of Fresno | 6302 W Spruce Ave | 1,329.68 Post Construction |
| 19 | Mow-N-Edge Corporation | 2002 Developed Basin Maint | 562.49 Post Construction |
| 19 | Mow-N-Edge Corporation | 2002 Developed Basin Maint | 49.00 Post Construction |
| 20 | Wildlife Control Technology | Agreement #2002-04 | 60.00 Post Construction |
| 19 | Mow-N-Edge Corporation | 09/2002 Developed Basin Mainte | 562.49 Post Construction |
| 20 | Wildlife Control Technology | Agreement #2002-04 | 60.00 Post Construction |
| 23 | City of Fresno | 6302 W Spruce Ave | 1,048.86 Post Construction |
| 19 | Mow-N-Edge Corporation | 10/2002 Developed Basin Mainte | 562.49 Post Construction |
| 19 | Mow-N-Edge Corporation | 11/2002 Developed Basin Mainte | 562.49 Post Construction |
| 20 | Wildlife Control Technology | Agreement #2002-04 | 60.00 Post Construction |
| 23 | City of Fresno | 6302 W Spruce Ave | 223.42 Post Construction |
| 19 | Mow-N-Edge Corporation | 12/2002 Developed Basin Mainte | 562.49 Post Construction |
| 20 | Wildlife Control Technology | Agreement #2002-04 | 60.00 Post Construction |
| 20 | Wildlife Control Technology | Agreement #2002-04 | 60.00 Post Construction |
| 19 | Mow-N-Edge Corporation | 01/2003 Developed Basin Mainte | 573.73 Post Construction |
| 19 | Mow-N-Edge Corporation | 2003 Developed Basin Maint Uni | 573.73 Post Construction |
| 23 | City of Fresno | 6302 W Spruce Ave | 115.62 Post Construction |
| 20 | Wildlife Control Technology | Agreement #2002-04 | 60.00 Post Construction |
| 24 | Mow-N-Edge Corporation | Dev Unit II Extra Work | 104.13 Post Construction |
| 24 | Mow-N-Edge Corporation | Dev Unit II | 573.73 Post Construction |
| 21 | Wildlife Control Technology | 2003 Rodent Control Srvc | 60.00 Post Construction |
| 23 | City of Fresno | 6302 W Spruce Ave | 128.46 Post Construction |
| 19 | Mow-N-Edge Corporation | 2003 Developed Basin Maint Uni | 573.73 Post Construction |
| 21 | Wildlife Control Technology | 4/2003 Rodent Control | 60.00 Post Construction |
| 19 | Mow-N-Edge Corporation | 2003 Developed Basin Maint Uni | 573.73 Post Construction |
| 21 | Wildlife Control Technology | 5/2003 Rodent Control | 60.00 Post Construction |
| 23 | City of Fresno | 6302 W Spruce Ave | 592.84 Post Construction |
| 19 | Mow-N-Edge Corporation | 6/03 Dev Basin Maint-Unit 2 | 573.73 Post Construction |
| 21 | Wildlife Control Technology | 6/2003 Rodent Control | 60.00 Post Construction |
| 19 | Lucas Weed Control, LLC | 07/2002 Undeveloped Basin Main | 102.50 Post Construction |
| 20 | Wildlife Control Technology | Agreement #2002-04 | 60.00 Post Construction |
| 19 | Lucas Weed Control, LLC | 08/2002 Undeveloped Basin Main | 102.50 Post Construction |
| 20 | Wildlife Control Technology | Agreement #2002-04 | 60.00 Post Construction |
| 20 | Wildlife Control Technology | Agreement #2002-04 | 60.00 Post Construction |
| 19 | Lucas Weed Control, LLC | 09/2002 Undeveloped Basin Main | 102.50 Post Construction |
| 20 | Wildlife Control Technology | Agreement #2002-04 | 60.00 Post Construction |
| 19 | Lucas Weed Control, LLC | 10/2002 Undeveloped Basin Main | 102.50 Post Construction |
| 19 | Lucas Weed Control, LLC | 11/2002 Undeveloped Basin Main | 102.50 Post Construction |
| 20 | Wildlife Control Technology | Agreement #2002-04 | 60.00 Post Construction |
| 19 | Lucas Weed Control, LLC | 12/2002 Undeveloped Basin Main | 102.50 Post Construction |
| 20 | Wildlife Control Technology | Agreement #2002-04 | 60.00 Post Construction |
| 19 | Irly-Bird Landscape Company | 01/2003 Undev Basin Maint | 68.95 Post Construction |
| 20 | Wildlife Control Technology | Agreement #2002-04 | 60.00 Post Construction |
| 19 | Irly-Bird Landscape Company | 2003 Undev Basin Maint Unit II | 68.95 Post Construction |
| 20 | Wildlife Control Technology | Agreement #2002-04 | 60.00 Post Construction |
| 21 | Wildlife Control Technology | 2003 Rodent Control Srvc | 60.00 Post Construction |
| 19 | Irly-Bird Landscape Company | 3/03 Undev Basin Maint Unit II | 68.95 Post Construction |
| 21 | Wildlife Control Technology | 4/2003 Rodent Control | 60.00 Post Construction |
| 19 | Irly-Bird Landscape Company | 4/03 Undev Basin Maint Unit II | 68.95 Post Construction |

**Table D-7. Continued.**

| | | | | | |
|---|---|---|---|---|---|
| | 21 | Wildlife Control Technology | 5/2003 Rodent Control | 60.00 | Post Construction |
| | 21 | Wildlife Control Technology | 6/2003 Rodent Control | 60.00 | Post Construction |
| | 19 | Lucas Weed Control, LLC | 07/2002 Undeveloped Basin Main | 38.68 | Post Construction |
| | 20 | Wildlife Control Technology | Agreement #2002-04 | 60.00 | Post Construction |
| | 19 | Lucas Weed Control, LLC | 08/2002 Undeveloped Basin Main | 38.68 | Post Construction |
| | 20 | Wildlife Control Technology | Agreement #2002-04 | 60.00 | Post Construction |
| | 20 | Wildlife Control Technology | Agreement #2002-04 | 60.00 | Post Construction |
| | 19 | Lucas Weed Control, LLC | 09/2002 Undeveloped Basin Main | 38.68 | Post Construction |
| | 20 | Wildlife Control Technology | Agreement #2002-04 | 60.00 | Post Construction |
| | 19 | Lucas Weed Control, LLC | 10/2002 Undeveloped Basin Main | 38.68 | Post Construction |
| | 19 | Lucas Weed Control, LLC | 11/2002 Undeveloped Basin Main | 38.68 | Post Construction |
| | 20 | Wildlife Control Technology | Agreement #2002-04 | 60.00 | Post Construction |
| | 19 | Lucas Weed Control, LLC | 12/2002 Undeveloped Basin Main | 38.68 | Post Construction |
| | 20 | Wildlife Control Technology | Agreement #2002-04 | 60.00 | Post Construction |
| | 19 | Irly-Bird Landscape Company | 01/2003 Undev Basin Maint | 2.94 | Post Construction |
| | 20 | Wildlife Control Technology | Agreement #2002-04 | 60.00 | Post Construction |
| | 19 | Irly-Bird Landscape Company | 2003 Undev Basin Maint Unit II | 2.94 | Post Construction |
| | 20 | Wildlife Control Technology | Agreement #2002-04 | 60.00 | Post Construction |
| | 21 | Wildlife Control Technology | 2003 Rodent Control Srvc | 60.00 | Post Construction |
| | 19 | Irly-Bird Landscape Company | 3/03 Undev Basin Maint Unit II | 2.94 | Post Construction |
| | 21 | Wildlife Control Technology | 4/2003 Rodent Control | 60.00 | Post Construction |
| | 19 | Irly-Bird Landscape Company | 4/03 Undev Basin Maint Unit II | 2.94 | Post Construction |
| | 21 | Wildlife Control Technology | 5/2003 Rodent Control | 60.00 | Post Construction |
| | 21 | Wildlife Control Technology | 6/2003 Rodent Control | 60.00 | Post Construction |
| | Item Number | | Total SWQM Detention Basins Operations & Maintenance | 17,980.16 | |
| Subtotal | 19 | | Undev/DevBasinMaint7051 | 8,174.05 | Post Construction |
| | 20 | | WildAgree2002-047051 | 2,460.00 | Post Construction |
| | 21 | | RodentControl7051 | 1,380.00 | Post Construction |
| | 22 | | CobbAgree2002-127051 | 290.00 | Post Construction |
| | 23 | | CitySpruceAve7051 | 3,438.88 | Post Construction |
| | 24 | | Misc7051 | 2,237.23 | Post Construction |
| | | | Total | 17,980.16 | |
| | | | Difference | 0.00 | |
| | | **SWQM Retention Basin Operations and Maintenance** | | | |
| | | Seibert's Oil Company Inc | 07/2002 Diesel Fuel | 114.50 | Post Construction |
| | | Seibert's Oil Company Inc | 07/2002 Diesel Fuel | 117.90 | Post Construction |
| | | Seibert's Oil Company Inc | 07/2002 Diesel Fuel | 115.33 | Post Construction |
| | | Seibert's Oil Company Inc | 08/2002 Diesel Fuel | 80.27 | Post Construction |
| | | Matthews & Son | Agreement #2002-01 | 1,630.50 | Post Construction |
| | | Matthews and Sons | Agreement #2002-01 | 35.00 | Post Construction |
| | | Safety Network | Equipment Rental | 180.00 | Post Construction |
| | | Safety Network | 7/21/02-8/02/02 Equip Rental | 253.00 | Post Construction |
| | | Chevron | Fuel | 9.86 | Post Construction |
| | | Cardlock Fuels System Inc | Fuel through 5/31/03 | 33.41 | Post Construction |
| | | Matthews and Sons | Agreement #2002-01 | 280.00 | Post Construction |
| | | R/C Matthews & Son | | 455.00 | Post Construction |
| | | Cardlock Fuels System Inc | 07/31/2002 Fuel | 9.53 | Post Construction |
| | | Matthews and Sons | Agreement #2002-01 | 4,345.13 | Post Construction |
| | | Video Inspection Specialists | Cleaning w/ Vacuum Truck | 435.00 | Post Construction |
| | | R/C Matthews and Sons | | 273.75 | Post Construction |
| | | R/C Matthews and Sons | | 542.50 | Post Construction |
| | | Cerutti & Sons Transportatio | Agreement #2002-09 | 290.55 | Post Construction |
| | | Matthews and Sons | Agreement #2002-01 | 180.84 | Post Construction |
| | | Emmetts Excavation Grading & | Agreement #2002-18 | 770.00 | Post Construction |
| | | Cardlock Fuels System Inc | 08/2002 Pump Fuel | 68.49 | Post Construction |
| | | Cardlock Fuels System Inc | 09/2002 Diesel | 59.49 | Post Construction |
| | | Cardlock Fuels System Inc | 10/15/2002 Pump Fuel/Truck Fue | 28.27 | Post Construction |
| | | Cardlock Fuels System Inc | 10/31/2002 Diesel Fuel | 15.02 | Post Construction |
| | | Cerutti & Sons Transportatio | Agreement #2002-09 | 961.05 | Post Construction |
| | | Matthews and Sons | Agreement #2002-01 | 180.83 | Post Construction |
| | | Emmetts Excavation Grading & | Agreement #2002-18 | 770.00 | Post Construction |
| | | Cardlock Fuels System Inc | 08/2002 Pump Fuel | 62.98 | Post Construction |
| | | Cardlock Fuels System Inc | 08/2002 Truck Fuel | 7.14 | Post Construction |

**Table D-7. Continued.**

| | | | | | |
|---|---|---|---|---|---|
| | | Cardlock Fuels System Inc | 09/2002 Diesel Fuel | 40.49 | Post Construction |
| | | Cardlock Fuels System Inc | 09/2002 Diesel | 389.47 | Post Construction |
| | | Cardlock Fuels System Inc | 10/15/2002 Pump Fuel/Truck Fue | 28.26 | Post Construction |
| | | Cardlock Fuels System Inc | 10/31/2002 Diesel Fuel | 20.16 | Post Construction |
| | | Cardlock Fuels System Inc | 09/2002 Diesel Fuel | 29.62 | Post Construction |
| | | R/C Matthews & Son | | 350.00 | Post Construction |
| | | R/C Matthews and Sons | | 245.00 | Post Construction |
| | | Matthews and Sons | Agreement #2002-01 | 1,487.50 | Post Construction |
| | | Video Inspection Specialists | Cleaning w/ Vacuum Truck | 580.00 | Post Construction |
| | | R/C Matthews and Sons | | 262.50 | Post Construction |
| | | E & J Gallo Winery | Greenwaste Deliveries | 1,155.00 | Post Construction |
| | | Matthews and Sons | Agreement #2002-01 | 7,731.25 | Post Construction |
| | | Matthews and Sons | Agreement #2002-01 | 326.26 | Post Construction |
| | | E & J Gallo Winery | 09/2002 Greenwaste Deliveries | 1,195.00 | Post Construction |
| | | Matthews and Sons | Agreement #2002-01 | 611.25 | Post Construction |
| | | E & J Gallo Winery | 11/2002 Greenwaste | 15.00 | Post Construction |
| | | Cerutti & Sons Transportatio | Agreement #2002-09 | 573.65 | Post Construction |
| | | Matthews and Sons | Agreement #2002-01 | 180.83 | Post Construction |
| | | Emmetts Excavation Grading & | Agreement #2002-18 | 1,020.00 | Post Construction |
| | **Item Number** | | **Total SWQM Retention Basin O&M** | **28,546.58** | |
| Subtotal | 25 | | Fuel7052 | 1,230.19 | Post Construction |
| | 26 | | M&SAgree2002-017052 | 16,989.39 | Post Construction |
| | 27 | | EquipRental7052 | 433.00 | Post Construction |
| | 28 | | Greenwaste7052 | 2,365.00 | Post Construction |
| | 29 | | CleaningVacuumTruck7052 | 1,015.00 | Post Construction |
| | 30 | | M&SBlank7052 | 2,128.75 | Post Construction |
| | 31 | | CeruttiAgree2002-097052 | 1,825.25 | Post Construction |
| | 32 | | EmmettsAgree2002-187052 | 2,560.00 | Post Construction |
| | | | Total | 28,546.58 | |
| | | | Difference | 0.00 | |
| | | **SWQM Structures Operations and Maintenance** | | | |
| | 33 | Video Inspection Specialists | 12/2002 Vacuum Truck Cleaning | 24.17 | Pollution Prevention |
| | 33 | Video Inspection Specialists | 12/2002 Vacuum Truck Cleaning | 290.00 | Pollution Prevention |
| | 33 | Video Inspection Specialists | 11/2002 Vacuum Cleaning | 435.00 | Pollution Prevention |
| | 33 | Video Inspection Specialists | 11/2002 Vacuum Cleaning | 330.00 | Pollution Prevention |
| | 33 | Video Inspection Specialists | 11/2002 Cleaning & Root Cuttin | 330.00 | Pollution Prevention |
| | 33 | Video Inspection Specialists | 10/2002 Vacuum Cleaning | 217.50 | Pollution Prevention |
| | 33 | Video Inspection Specialists | Cleaning w/ Vacuum Truck | 362.50 | Pollution Prevention |
| | 33 | Video Inspection Specialists | Clean w/Vacuum Truck | 1,550.00 | Pollution Prevention |
| | 33 | Video Inspection Specialists | 12/2002 Vacuum Truck Cleaning | 217.50 | Pollution Prevention |
| | 33 | Video Inspection Specialists | 12/2002 Vacuum Truck Cleaning | 145.00 | Pollution Prevention |
| | 33 | Video Inspection Specialists | 12/2002 Vacuum Truck Cleaning | 24.17 | Pollution Prevention |
| | 33 | Video Inspection Specialists | 11/2002 Vacuum Cleaning | 290.00 | Pollution Prevention |
| | 33 | Video Inspection Specialists | Clean w/Vacuum Truck & TV Insp | 2,195.00 | Pollution Prevention |
| | 34 | City of Fresno | 7/02-3/03 Pipeline Maint | 288.10 | Pollution Prevention |
| | 34 | City of Fresno | 7/02-3/03 Pipeline Maint | 296.10 | Pollution Prevention |
| | 33 | Video Inspection Specialists | 10/2002 Vacuum Cleaning | 217.50 | Pollution Prevention |
| | 33 | Video Inspection Specialists | 12/2002 Vacuum Truck Cleaning | 145.00 | Pollution Prevention |
| | 33 | Video Inspection Specialists | 12/2002 Vacuum Truck Cleaning | 24.16 | Pollution Prevention |
| | 34 | City of Fresno | 7/02-3/03 Pipeline Maint | 72.36 | Pollution Prevention |
| | 33 | Video Inspection Specialists | 12/2002 Vacuum Cleaning | 362.50 | Pollution Prevention |
| | 33 | Video Inspection Specialists | 10/2002 Vacuum Cleaning | 217.50 | Pollution Prevention |
| | 33 | Video Inspection Specialists | 03/2003 Vacuum Truck Cleaning | 310.00 | Pollution Prevention |
| | 33 | Video Inspection Specialists | 11/2002 Vacuum Cleaning | 145.00 | Pollution Prevention |
| | 33 | Video Inspection Specialists | 11/2002 Vacuum Cleaning | 580.00 | Pollution Prevention |
| | 33 | Video Inspection Specialists | 11/2002 Cleaning & Root Cuttin | 290.00 | Pollution Prevention |
| | 33 | Video Inspection Specialists | 12/2002 Vacuum Cleaning | 507.50 | Pollution Prevention |
| | 33 | Video Inspection Specialists | Clean w/Vacuum Truck | 310.00 | Pollution Prevention |
| | **Item Number** | | **Total SWQM Structures O&M** | **10,176.56** | |
| Subtotal | 33 | | VISTruckCleaning7054 | 9,520.00 | Pollution Prevention |
| | 34 | | FresnoPipeline7054 | 656.56 | Pollution Prevention |
| | | | Total | 10,176.56 | |
| | | | Difference | 0.00 | |

**Table D-7. Continued.**

| | | | | | |
|---|---|---|---|---|---|
| | **SWQM Pump Operations and Maintenance** | | | | |
| | 35 | Video Inspection Specialists | Clean w/Vacuum Truck | 155.00 | Pollution Prevention |
| | 35 | Video Inspection Specialists | 7/2002 Pump Station Vacuum Clo | 580.00 | Pollution Prevention |
| | 35 | Video Inspection Specialists | 7/2002 Pump Station Vacuum Clc | 507.50 | Pollution Prevention |
| | 35 | Video Inspection Specialists | 11/2002 Cleaning & Root Cuttin | 742.50 | Pollution Prevention |
| | 35 | Video Inspection Specialists | Clean w/Vacuum Truck | 787.50 | Pollution Prevention |
| | 35 | Video Inspection Specialists | 11/2002 Vacuum Cleaning | 253.75 | Pollution Prevention |
| | 35 | Video Inspection Specialists | Clean w/Vacuum Truck | 310.00 | Pollution Prevention |
| | 35 | Video Inspection Specialists | 11/2002 Cleaning & Root Cuttin | 330.00 | Pollution Prevention |
| | 35 | Video Inspection Specialists | Clean w/Vacuum Truck | 232.50 | Pollution Prevention |
| | 35 | Video Inspection Specialists | 03/2003 Vacuum Truck Cleaning | 290.00 | Pollution Prevention |
| | 35 | Video Inspection Specialists | 11/2002 Vacuum Cleaning | 217.50 | Pollution Prevention |
| | 35 | Video Inspection Specialists | 10/2002 Vacuum Cleaning | 217.50 | Pollution Prevention |
| | 35 | Video Inspection Specialists | 10/2002 Vacuum Cleaning | 290.00 | Pollution Prevention |
| | 35 | Video Inspection Specialists | 10/2002 Vacuum Cleaning | 72.50 | Pollution Prevention |
| | 35 | Video Inspection Specialists | 10/2002 Vacuum Cleaning | 580.00 | Pollution Prevention |
| | 35 | Video Inspection Specialists | 10/2002 Vacuum Cleaning | 72.50 | Pollution Prevention |
| | 36 | Pacific Gas & Electric Compa | 10/03/02-11/18/02 Service | 49.49 | Pollution Prevention |
| | 36 | Pacific Gas & Electric Compa | Service through 12/17/2002 | 32.56 | Pollution Prevention |
| | 36 | Pacific Gas & Electric Compa | Service thru 10/12/02-01/03/03 | 51.17 | Pollution Prevention |
| | 36 | Pacific Gas & Electric Compa | Service thru 04/17/03 | 7.67 | Pollution Prevention |
| | 36 | Pacific Gas & Electric Compa | Service thru 05/12/03 Pump Sit | 28.67 | Pollution Prevention |
| | 36 | Pacific Gas & Electric Compa | Service through 7/18/03 | 86.03 | Pollution Prevention |
| | 36 | Pacific Gas & Electric Compa | Service through 6/18/03 | 86.03 | Pollution Prevention |
| | 36 | Pacific Gas & Electric Compa | 07/03/02-08/02/02 Service | 10.80 | Pollution Prevention |
| | 36 | Pacific Gas & Electric Compa | 08/02/02-09/03/02 Service | 10.80 | Pollution Prevention |
| | 36 | Pacific Gas & Electric Compa | 09/03/02-10/02/02 Service | 10.80 | Pollution Prevention |
| | 36 | Pacific Gas & Electric Compa | 10/02/02-10/31/02 Service | 10.80 | Pollution Prevention |
| | 36 | Pacific Gas & Electric Compa | 10/31/02-11/27/02 Service | 11.50 | Pollution Prevention |
| | 36 | Pacific Gas & Electric Compa | Service thru 10/12/02-01/03/03 | 12.98 | Pollution Prevention |
| | 36 | Pacific Gas & Electric Compa | 10/12/02-01/03/03 Service | 14.22 | Pollution Prevention |
| | 36 | Pacific Gas & Electric Compa | 03/2003 Site Pump Utilities | 12.47 | Pollution Prevention |
| | 36 | Pacific Gas & Electric Compa | Service thru 04/10/03 Pump Sit | 11.94 | Pollution Prevention |
| | 36 | Pacific Gas & Electric Compa | Service thru 05/12/03 Pump Sit | 11.91 | Pollution Prevention |
| | 36 | Pacific Gas & Electric Compa | Service thru 06/11/03 Pump Sit | 22.37 | Pollution Prevention |
| | 36 | Pacific Gas & Electric Compa | Service thru 7/11/03 | 10.29 | Pollution Prevention |
| | 36 | Pacific Gas & Electric Compa | 07/03/02-08/02/02 Service | 126.05 | Pollution Prevention |
| | 36 | Pacific Gas & Electric Compa | 08/02/02-09/03/02 Service | 79.22 | Pollution Prevention |
| | 36 | Pacific Gas & Electric Compa | 09/03/02-10/02/02 Service | 76.74 | Pollution Prevention |
| | 36 | Pacific Gas & Electric Compa | 10/02/02-10/31/02 Service | 57.03 | Pollution Prevention |
| | 36 | Pacific Gas & Electric Compa | 10/31/02-11/27/02 Service | 24.12 | Pollution Prevention |
| | 36 | Pacific Gas & Electric Compa | Service thru 10/12/02-01/03/03 | 10.29 | Pollution Prevention |
| | 36 | Pacific Gas & Electric Compa | 10/12/02-01/03/03 Service | 11.36 | Pollution Prevention |
| | 36 | Pacific Gas & Electric Compa | 03/2003 Site Pump Utilities | 10.65 | Pollution Prevention |
| | 36 | Pacific Gas & Electric Compa | Service thru 04/10/03 Pump Sit | 10.65 | Pollution Prevention |
| | 36 | Pacific Gas & Electric Compa | Service thru 05/12/03 Pump Sit | 11.39 | Pollution Prevention |
| | 36 | Pacific Gas & Electric Compa | Service thru 06/11/03 Pump Sit | 13.46 | Pollution Prevention |
| | 36 | Pacific Gas & Electric Compa | Service thru 7/11/03 | 83.81 | Pollution Prevention |
| | 35 | Video Inspection Specialists | 10/2002 Vacuum Cleaning | 145.00 | Pollution Prevention |
| | 35 | Video Inspection Specialists | 11/2002 Vacuum Cleaning | 108.75 | Pollution Prevention |
| | 35 | Video Inspection Specialists | 11/2002 Vacuum Cleaning | 181.25 | Pollution Prevention |
| | 35 | Video Inspection Specialists | Clean w/Vacuum Truck | 155.00 | Pollution Prevention |
| | Item Number | | **Total SWQM Pump O&M** | 7,236.02 | |
| Subtotal | 35 | | VISTruckCleaning7055 | 6,228.75 | Pollution Prevention |
| | 36 | | PGEService7055 | 1,007.27 | Pollution Prevention |
| | | | Total | 7,236.02 | |
| | | | Difference | 0.00 | |
| **SWQM Other Operations and Maintenance** | | | | | |
| | 37 | Melco Fence | 02/2003 Fence Repair | 584.00 | Post Construction |
| | **SWQM Soil Monitoring** | | | | |
| | 38 | BSK Analytical Laboratories | Low Level Lead Profile | 297.00 | Post Construction |
| | 38 | BSK Analytical Laboratories | 07/10/2002 Low Level Lead Prof | 99.00 | Post Construction |
| | 38 | BSK Analytical Laboratories | Low Level Lead Profile | 396.00 | Post Construction |
| | 38 | BSK Analytical Laboratories | 07/2002 Low Level Lead Profile | 363.00 | Post Construction |
| | 38 | BSK Analytical Laboratories | 07/2002 Low Level Lead Profile | 264.00 | Post Construction |
| | 38 | BSK Analytical Laboratories | 07/03/2002 Low Level Lead Prof | 198.00 | Post Construction |
| | 38 | BSK Analytical Laboratories | Low Level Lead Profile | 363.00 | Post Construction |
| | 38 | BSK Analytical Laboratories | 08/2002 Low Level Lead Profile | 99.00 | Post Construction |
| | 38 | BSK Analytical Laboratories | Low Level Lead Profile | 198.00 | Post Construction |
| | 38 | BSK Analytical Laboratories | 07/03/2002 Low Level Lead Prof | 66.00 | Post Construction |
| | 38 | BSK Analytical Laboratories | Low Level Lead Profile | 132.00 | Post Construction |
| | 38 | BSK Analytical Laboratories | 07/10/2002 Low Level Lead Prof | 99.00 | Post Construction |
| | 38 | BSK Analytical Laboratories | 07/11/2002 Low Level Lead Prof | 396.00 | Post Construction |
| | 38 | BSK Analytical Laboratories | 07/15/2002 Low Level Lead Prof | 396.00 | Post Construction |
| | 38 | BSK Analytical Laboratories | Low Level Lead Profile | 396.00 | Post Construction |
| | 38 | BSK Analytical Laboratories | Low Level Lead Profile | 198.00 | Post Construction |
| | 38 | BSK Analytical Laboratories | 07/10/2002 Low Level Lead Prof | 99.00 | Post Construction |
| | 38 | BSK Analytical Laboratories | 07/10/2002 Low Level Lead Prof | 99.00 | Post Construction |
| | 38 | BSK Analytical Laboratories | 07/2002 Low Level Lead Profile | 132.00 | Post Construction |
| | 38 | BSK Analytical Laboratories | 07/2002 Low Level Lead Profile | 99.00 | Post Construction |
| | 38 | BSK Analytical Laboratories | Low Level Lead Profile-II3 | 165.00 | Post Construction |
| | 38 | BSK Analytical Laboratories | 07/2002 Low Level Lead Profile | 396.00 | Post Construction |
| | 38 | BSK Analytical Laboratories | 08/2002 Low Level Lead Profile | 264.00 | Post Construction |
| | 38 | BSK Analytical Laboratories | Low Level Lead Profile | 198.00 | Post Construction |

**Table D-7. Continued.**

| Item Number | Vendor | Description | Amount | Category |
|---|---|---|---|---|
| 38 | BSK Analytical Laboratories | Low Level Lead Profile | 198.00 | Post Construction |
| 38 | BSK Analytical Laboratories | 10/2002 Low Level Lead Profile | 396.00 | Post Construction |
| 38 | BSK Analytical Laboratories | 11/2002 Low Level Lead Profile | 99.00 | Post Construction |
| 38 | BSK Analytical Laboratories | 10/2002 Low Level Lead Profile | 99.00 | Post Construction |
| 38 | BSK Analytical Laboratories | 11/2002 Low Level Lead Profile | 99.00 | Post Construction |
| 38 | BSK Analytical Laboratories | 07/2002 Low Level Lead Profile | 99.00 | Post Construction |
| 38 | BSK Analytical Laboratories | 09/2002 Low Level Lead Profile | 297.00 | Post Construction |
| 38 | BSK Analytical Laboratories | 09/2002 Low Level Lead Profile | 231.00 | Post Construction |
| 38 | BSK Analytical Laboratories | 08/2002 Low Level Lead Profile | 396.00 | Post Construction |
| 38 | BSK Analytical Laboratories | 08/2002 Low Level Lead Profile | 198.00 | Post Construction |
| 38 | BSK Analytical Laboratories | 09/2002 Low Level Lead Profile | 198.00 | Post Construction |
| 38 | BSK Analytical Laboratories | 07/2002 Low Level Lead Profile | 396.00 | Post Construction |
| 38 | BSK Analytical Laboratories | 07/2002 Low Level Lead Profile | 297.00 | Post Construction |
| 38 | BSK Analytical Laboratories | 08/2002 Low Level Lead Profile | 279.00 | Post Construction |
| 38 | BSK Analytical Laboratories | Low Level Lead Profile-Bal Due | 18.00 | Post Construction |
| 38 | BSK Analytical Laboratories | 07/10/2002 Low Level Lead Prof | 231.00 | Post Construction |
| 38 | BSK Analytical Laboratories | 07/2002 Low Level Lead Profile | 231.00 | Post Construction |
| 38 | BSK Analytical Laboratories | 08/2002 Low Level Lead Profile | 66.00 | Post Construction |
| 38 | BSK Analytical Laboratories | 09/2002 Low Level Lead Profile | 198.00 | Post Construction |
| 38 | BSK Analytical Laboratories | 05/2002 Low Level Lead Profile | 165.00 | Post Construction |
| 38 | BSK Analytical Laboratories | 08/2002 Low Level Lead Profile | 297.00 | Post Construction |
| 38 | BSK Analytical Laboratories | 10/2002 Low Level Lead Profile | 99.00 | Post Construction |
| 38 | BSK Analytical Laboratories | 11/2002 Low Level Lead Profile | 99.00 | Post Construction |
| 38 | BSK Analytical Laboratories | 05/2002 Low Level Lead Profile | 165.00 | Post Construction |
| 38 | BSK Analytical Laboratories | 05/2002 Low Level Lead Profile | 165.00 | Post Construction |
| 38 | | **Total SWQM Soil Monitoring** | 10,428.00 | Post Construction |

**Municipal NPDES Program Implementation 7060-7066**

**Investigation, Inspection, Enforcement**

| Item Number | Vendor | Description | Amount | Category |
|---|---|---|---|---|
| 39 | Fotech Color Labs | 08/2002 Photos | 6.00 | Illicit Discharge |
| 39 | Fotech Color Labs | 07/2002 Photos | 16.66 | Illicit Discharge |
| 39 | Fotech Color Labs | Photo Developing | 53.83 | Illicit Discharge |
| 39 | | **Total Investigation, Inspection, Enforcement** | 76.49 | Illicit Discharge |

**Monitoring**

| Item Number | Vendor | Description | Amount | Category |
|---|---|---|---|---|
| 42 | AirLink Communications | 08/2002 IP Activation Fee | 45.00 | Monitoring |
| 41 | AT&T Wireless Services | 07/14/2002-08/13/2002 Services | 26.18 | Monitoring |
| 40 | Larry Walker Associates Inc | Storm Water Quality Monitoring | 10,552.33 | Monitoring |
| 41 | AT&T Wireless Services | 08/14/02-09/13/02 Service Peri | 23.76 | Monitoring |
| 42 | AirLink Communications | 07/24/02-08/23/02 Telemetry Fe | 58.06 | Monitoring |
| 40 | Larry Walker Associates Inc | 2002-2003 Stormwater Monitorin | 1,823.85 | Monitoring |
| 40 | Larry Walker Associates Inc | 2001-2002 Stormwater Monitorin | 8,756.96 | Monitoring |
| 40 | Larry Walker Associates Inc | 2001-2002 Stormwater Monitorin | 3,192.74 | Monitoring |
| 42 | AirLink Communications | 10/2002 Telemetry Monthly Fee | 98.00 | Monitoring |
| 41 | AT&T Wireless Services | 09/14/02-10/13/02 Service | 23.35 | Monitoring |
| 42 | Airlink Communications Inc | 09/24/02-10/23/02 Monthly Fee | 98.00 | Monitoring |
| 41 | AT&T Wireless Services | 10/14/02-11/13/02 Service | 23.98 | Monitoring |
| 43 | Larry Walker Associates Inc | 10/01/02-10/31/02 Professional | 7,816.19 | Monitoring |
| 43 | Larry Walker Associates Inc | 09/01/02-09/18/02 Professional | 4,692.12 | Monitoring |
| 40 | Larry Walker Associates Inc | 2002-2003 SWQ Monitoring | 18,662.34 | Monitoring |
| 42 | Airlink Communications Inc | Service through 11/23/2002 | 98.00 | Monitoring |
| 41 | AT&T Wireless Services | Service through 12/13/2002 | 23.56 | Monitoring |
| 41 | AT&T Wireless Services | Service thru 01/15/2003 | 23.46 | Monitoring |
| 43 | Larry Walker Associates Inc | Service thru 12/31/2002 | 27,576.10 | Monitoring |
| 42 | Airlink Communications Inc | Services thru 12/23/2002 | 98.00 | Monitoring |
| 41 | AT&T Wireless Services | Service thru 02/13/03 | 25.75 | Monitoring |
| 40 | Larry Walker Associates Inc | 2002-2003 SWQ Monitoring | 17,728.24 | Monitoring |
| 42 | Airlink Communications Inc | Service thru 01/23/03 | 98.00 | Monitoring |
| 42 | Airlink Communications Inc | 02/23/03 Monthly Fee | 98.00 | Monitoring |
| 41 | AT&T Wireless Services | 03/15/03 Billing | 23.61 | Monitoring |
| 40 | Larry Walker Associates Inc | 02/2003 SWQ Monitoring | 14,544.32 | Monitoring |



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**Table D-7. Continued.**

| | | | | |
|---|---|---|---|---|
| | 41 AT&T Wireless Services | Service thru 04/13/03 | 21.18 | Monitoring |
| | 40 Larry Walker Associates Inc | 02-03 Storm Water Monitoring | 14,464.70 | Monitoring |
| | 42 Airlink Communications Inc | IP Local - Unlimited | 98.00 | Monitoring |
| | 42 Airlink Communications Inc | IP Local Unlimited | 98.00 | Monitoring |
| | 41 AT&T Wireless Services | Service Through 5/13/2003 | 23.24 | Monitoring |
| | 40 Larry Walker Associates Inc | 02-03 Storm Water Monitoring | 17,532.15 | Monitoring |
| | 44 Water Env Research Foundatio | 03/04 Subscription to WERF | 10,000.00 | Monitoring |
| | 40 Larry Walker Associates Inc | 02-03 Stormwater Quality Monit | 12,274.56 | Monitoring |
| | 42 Airlink Communications Inc | IP Usage through 6/23/03 | 98.00 | Monitoring |
| | 42 Airlink Communications Inc | IP Local Service through 5/23/ | 98.00 | Monitoring |
| | 41 AT&T Wireless Services | Service through 6/15/2003 | 22.42 | Monitoring |
| | 41 AT&T Wireless Services | Service through 7/13/03 | 21.50 | Monitoring |
| | 40 Larry Walker Associates Inc | 02-03 Stormwater Monitoring | 24,331.20 | Monitoring |
| | Item Number | Total Monitoring | 195,312.85 | |
| Subtotal | 40 | LWASWQM7063 | 143,863.39 | Monitoring |
| | 41 | ATTService7063 | 281.99 | Monitoring |
| | 42 | AirlinkIP7063 | 1,083.06 | Monitoring |
| | 43 | LWAProf7063 | 40,084.41 | Monitoring |
| | 44 | WERF7063 | 10,000.00 | Monitoring |
| | | Total | 195,312.85 | |
| | | Difference | 0.00 | |
| | **Public Information** | | | |
| | 45 Cash | Vons | 10.70 | Management |
| | 46 David J Pomaville | Clean Water Award Reimbursemen | 22.62 | Public Education |
| | 46 Pro Image Video LLC | Transfer PSA from VHS to Digit | 276.97 | Public Education |
| | 48 Bank of America | Office Depot | 55.16 | Management |
| | 46 Pro Image Video LLC | 08/2002 Duplicate PSA VHS Tape | 21.58 | Public Education |
| | 46 Fotech Color Labs | Dev & Prints | 18.72 | Public Education |
| | 52 River Parkway Trust | Reimbursement Storm Water Gran | 1,920.00 | Public Education |
| | 45 Cash | Casa Valadez Mexican Restauran | 12.40 | Management |
| | 46 Panagraph Inc | 2002-2003 SWQMP Public Info & | 255.00 | Public Education |
| | 47 Fotech Color Labs | 09/2002 Dev & Print | 7.51 | Management |
| | 48 Fresno Ag Hardware | 09/2002 Supplies | 4.80 | Management |
| | 46 San Joaquin River Parkway | Clean Storm Water Grant Reimb | 1,899.45 | Public Education |
| | 45 Bank of America | Vons Grocery Store | 11.49 | Management |
| | 45 Bank of America | Vons Grocery Store | 24.33 | Management |
| | 48 Cash | Orchard Supply | 5.18 | Management |
| | 45 Cash | Riverfest 2002 Food | 15.50 | Management |
| | 47 Prestige Printing | 10/2002 Letterheads-Storm Wate | 606.26 | Management |
| | 48 Bank of America | Office Max | 28.80 | Management |
| | 56 San Joaquin River Parkway Tr | Fresno City Parks & Rec CSW Gr | 1,000.00 | Management |
| | 46 City Press | 10/2002 Action Alert Flyers | 625.00 | Public Education |
| | 46 City Press | 10/2002 Action Alert Flyers | 49.22 | Public Education |
| | 45 Bank of America | Vons | 44.98 | Management |
| | 49 SWRCB | Waste Discharge Req Annual Fee | 1,500.00 | Management |
| | 49 SWRCB | Waste Discharge Req Annual Fee | 10,000.00 | Management |
| | 49 SWRCB | Waste Discharge Req Annual Fee | 2,500.00 | Management |
| | 49 SWRCB | Waste Discharge Req Annual Fee | 3,750.00 | Management |
| | 46 Bank of America | Kinko's | 224.10 | Public Education |
| | 48 Bank of America | OfficeMax | 37.65 | Management |
| | 45 Bank of America | Bobby Salazar's | 29.35 | Management |
| | 56 Bank of America | Env-Sol-Com | 203.00 | Management |
| | 52 River Parkway Trust | Clean Storm Water Grant Reimb | 50.00 | Public Education |
| | 50 Daniel P Rourke | Mileage Reimbursement | 85.05 | Management |
| | 46 Pro Image Video LLC | 12/2002 Public Information | 149.08 | Public Education |
| | 45 Bank of America | Bobby Salazars | 37.87 | Management |
| | 56 Bank of America | Amazon.Com | 232.20 | Management |
| | 50 Bank of America | Hyatt Regency Monterey | 297.68 | Management |
| | 45 Cash | SaveMart Supermarkets | 9.14 | Management |
| | 50 Daniel P Rourke | Ineligible Portion-Hyatt | -4.28 | Management |
| | 51 Daniel P Rourke | CWEA Conference-Peninsula Rest | 22.50 | Management |
| | 50 Daniel P Rourke | CWEA Conference Mileage Reimb | 115.20 | Management |
| | 51 Daniel P Rourke | CWEA Conference-Goomba's Kitch | 19.00 | Management |
| | 51 Daniel P Rourke | CWEA Conference-Jugem Japanese | 13.89 | Management |

**Table D-7. Continued.**

| | | | | |
|---|---|---|---|---|
| 46 | Panagraph Inc | Service thru 01/2003 | 2,015.13 | Public Education |
| 46 | City Press | 02/2003 Storm Water Pollution | 1,048.39 | Public Education |
| 51 | Daniel P Rourke | 03/2003 WRPPN Meetings-040-LJX | 11.50 | Management |
| 51 | Daniel P Rourke | WRPPN Committee Meeting-Zocalo | 12.50 | Management |
| 51 | Daniel P Rourke | 03/2003 WRPPN Meetings-Hamburg | 13.04 | Management |
| 51 | Daniel P Rourke | WRPPN Committee Meeting-Hungry | 7.50 | Management |
| 46 | Panagraph Inc | 2002-2003 SWQMP | 382.50 | Public Education |
| 45 | Bank of America | Fresno Audio Visual - Vons | 24.70 | Management |
| 56 | Bank of America | Fresno Audio Visual - Cinnamon | 141.25 | Management |
| 56 | Bank of America | Fresno Audio Visual - Mariscos | 24.92 | Management |
| 45 | Bank of America | Fresno Audio Visual - Food 4 L | 2.85 | Management |
| 56 | Bank of America | OSH-Brass Grommet | 25.94 | Management |
| 56 | Bank of America | Fresno Audio Visual - DiCiccos | 65.59 | Management |
| 56 | Bank of America | Fresno Audio Visual - Cinnamon | 47.00 | Management |
| 45 | Bank of America | Fresno Audio Visual - Vons | 17.85 | Management |
| 56 | Bank of America | Fresno Audio Visual - Draper S | 18.32 | Management |
| 56 | Cash | Fresno Pollution Prevention Gr | 16.53 | Management |
| 52 | Central Unified School Distr | 2003 Clean Storm Water Grant | 1,527.49 | Public Education |
| 48 | Fresno Ag Hardware | Devoe Traffic Gal/Pail/Bucket | 40.27 | Management |
| 52 | Liberty Elementary | 2003 Clean Storm Water Grant | 52.00 | Public Education |
| 54 | Daniel P Rourke | CASQA-BMP Handbook Workshop | 27.40 | Management |
| 52 | Liberty Elementary | Clean Storm Water Grant | 68.00 | Public Education |
| 56 | Bank of America | Vons-Me n Eds-Intergrated Pest | 50.65 | Management |
| 46 | Panagraph Inc | Services thru 03/2003 | 616.25 | Public Education |
| 56 | Asian Pacific American Herit | Booth Space/Sponsorship | 250.00 | Management |
| 47 | Cash | Aerial Photocopies | 2.00 | Management |
| 46 | Zoo Lynx | 2003 Earth Day Ad & Clean Up | 965.00 | Public Education |
| 47 | Airport Blueprint Inc | Aerial Photos | 5.83 | Management |
| 55 | Consolidated Printworks | Utility Bill Inserts | 316.00 | Public Education |
| 46 | Panagraph Inc | SWQMP Public Info & Education | 38,102.22 | Public Education |
| 52 | UC Regents | Clean Storm Water Grant | 2,000.00 | Public Education |
| 54 | Bank of America | El Pollo-CASQA BMP Handbook Mt | 6.80 | Management |
| 54 | Bank of America | CASQA BMP Handbook Workshop | 25.00 | Management |
| 53 | Bank of America | Hertz-SWQ BMP Training | 152.95 | Management |
| 53 | Bank of America | Hyatt-SWQ BMP Training | 95.58 | Management |
| 56 | Bank of America | The Upper Crust-SWQ BMP Traini | 13.21 | Management |
| 56 | Bank of America | The Thai House-GeoSyntec Meeti | 49.00 | Management |
| 56 | Bank of America | NTIS-EPA-Document | 56.00 | Management |
| 54 | Bank of America | Mariscos-CASQA BMP Handbook Mt | 7.01 | Management |
| 53 | Bank of America | Hyatt-SWQ BMP Training-Parking | 12.00 | Management |
| 53 | Bank of America | Hyatt-SWQ BMP Training-Meals | 40.09 | Management |
| 55 | City Press | Utility Bill Inserts | 1,097.74 | Public Education |
| 56 | Cash | Fresno Audio Visual | 21.04 | Management |
| 56 | Cash | Costco-Open Space Const | 67.39 | Management |
| 51 | Cash | Vons-Phase II Meeting | 11.83 | Management |
| 56 | Solon Manufacturing Co Inc | Paint Paddles | 6,829.59 | Management |
| 52 | Central High School-Env Scie | 2003 Clean Storm Water Grant | 1,823.87 | Public Education |
| 55 | City Press | Utility Bill Inserts | 1,111.18 | Public Education |
| 56 | City Press | Stormwater Pollution Packets | 878.60 | Management |
| 56 | City Press | Gardening Tips Bill Insert Cre | -296.05 | Management |
| 50 | Daniel P Rourke | Mileage Reimbursement | 108.36 | Management |
| 56 | State of CA-WRCB | | -2,500.00 | Management |
| 56 | Consolidated Printworks | Watering Schedule Insert | 222.93 | Management |
| 46 | Panagraph Inc | 02-03 Public Info & Education | 44,846.40 | Public Education |
| 56 | Bank of America | City of Fresno-Zoning Ordinanc | 25.00 | Management |
| 45 | Bank of America | Bobby Salazars-Lunch Meeting | 64.52 | Management |
| 56 | Bank of America | OSH-Garden Sprayer | 21.62 | Management |
| 45 | Bank of America | Javiers-Business Lunch | 35.00 | Management |
| 46 | Bank of America | Sir Speedy Printing-Clovis Zon | 20.55 | Public Education |
| 56 | Bank of America | Paper Plus-Environmental Fact | 40.93 | Management |
| 46 | City of Fresno Parks & Recre | 2002 Clean Storm Water Grant | 1,000.00 | Management |
| 46 | Jack Nadel, Inc | #2 Pencils/Screen Set Up Charg | 1,350.41 | Management |
| 46 | Linda Jacobsen | Clean Storm Water Grant Reimb | 43.11 | Management |
| 46 | Panagraph Inc | 06/2003 Services SWQMP Info | 2,445.61 | Management |
| 52 | San Joaquin River Parkway & | 2003 Clean Storm Water Grant | 80.00 | Management |

**Table D-7. Continued.**

| | Item Number | | Description | Amount | Category |
|---|---|---|---|---|---|
| | | | **Total Public Information** | 133,892.99 | |
| Subtotal | 45 | | Food7064 | 340.68 | Management |
| | 46 | | PublicEducation7064 | 96,377.31 | Public Education |
| | 47 | | Printing7064 | 621.60 | Management |
| | 48 | | OfficeSupplies7064 | 171.86 | Management |
| | 49 | | SWRCBFees7064 | 17,750.00 | Management |
| | 50 | | Travel7064 (Mileage, Hotels) | 602.01 | Management |
| | 51 | | ConferenceMeetings7064 | 111.76 | Management |
| | 52 | | Grant7064 | 7,521.36 | Public Education |
| | 53 | | Training7064 | 300.62 | Management |
| | 54 | | Handbooks7064 | 66.21 | Management |
| | 55 | | UtilityBill7064 | 2,524.92 | Public Education |
| | 56 | | Misc7064 | 7,504.66 | Management |
| | | | Total | 133,892.99 | |
| | | | Difference | 0.00 | |
| | | **General Expenses** | | 0.00 | |
| | | **Program Expenses** | | | |
| | 57 | Quercus Publications | Streams of the SJV Book | 55.50 | Management |
| | 57 | Bank of America | NTIS-Groundwater Contamination | 56.00 | Management |
| | Item Number 57 | | **Total Program Expenses** | 111.50 | Management |
| Industrial NPDES Program Implementation 7070-7076 | | | | | |
| | | **Investigation, Inspection, Enforcement** | | | |
| | 58 | City Press | Phone Complaints - Forms | 332.96 | Industrial |
| | | **Monitoring** | | 0.00 | |
| | | **Public Information** | | | |
| | 59 | The Business Journal | Newspaper Subscription | 88.00 | Public Education |
| | 59 | EXCAL Visual Communications | 08/2002 Storm Water Training K | 1,013.50 | Public Education |
| | 59 | Panagraph Inc | Services thru 12/2002 | 13,993.30 | Public Education |
| | Item Number 59 | | **Total Public Information** | 15,094.80 | Public Education |
| (Source: Rourke, pc, 3/23/04 | | | **Total of Subtotals** | $ 611,843.66 | |

1. Cost Categories Abbreviated According to the Following:
   - Construction: Construction Site Stormwater Runoff Control
   - Illicit Discharge: Illicit Discharge Detection and Elimination
   - Industrial: Industrial and Commercial Management Programs
   - Management: Overall Stormwater Program Management
   - Pollution Prevention: Pollution Prevention and Good Housekeeping for Municipal Operations
   - Post Construction: Post Construction Water Management in New Development and Redevelopment
   - Public Education: Public Education, Outreach, Involvement, and Participation
   - Monitoring: Water Quality Monitoring
   - Watershed: Watershed Management

The backup calculations for the cost for each cost survey category in Section 7 and the sources of the cost data are presented in this appendix. Tables are generally presented by sequentially increasing levels of detail. Figure E-1 illustrates how data is shared throughout the tables.

Table E-1 contains all costs organized into the various standard cost survey categories. The subtotals for each cost category are also presented in Section 7, Table 7-2. The remaining tables (E-2 through E-9) present the detailed back-up information for the numbers in Table E-1. Table E-1 is linked to the back-up tables by the table and item numbers in the 'Source' column. Most of the cost information provided by city staff is listed in Table E-2. Item numbers corresponding to the subtotals in Table E-2 were added to the left hand column to easily show how the numbers are pulled forward to Table E-1. The right hand column in Table E-2 was added to show how costs were allocated to the cost survey categories. Table E-1 entries that were not taken directly from Table E-2 are found in Tables E-3 through E-9.

For the city of Sacramento, labor costs are distributed among the various cost survey categories according to labor cost spreadsheets provided by city staff (Table E-7). Thus, comparing costs with other municipalities where such costs are not distributed, Sacramento's Overall Stormwater Management Program costs will be lower.

Detailed descriptions of how the costs were developed are contained in the following paragraphs.

### *Construction Site Stormwater Runoff Control*

The total cost for this category was $261,716. The costs for this category include labor, which was broken down into three categories: inspections, student interns, and all other activities. There was also cost identified for developing BMP handbooks (one time annual cost, but may occur at a time later than one year). Other activities performed included (descriptions obtained from annual stormwater report):

- Issued 144 grading permits
- Reviewed 68 SWPPPs
- Issued 384 enforcement actions
- Sent winterization letters to property owners with active construction sites to remind contractors to prepare their construction sites for the rainy season and to submit winterization certifications
- Developed a Microsoft Access database to track all stormwater inspections and enforcement actions for private development construction sites

## Sacramento

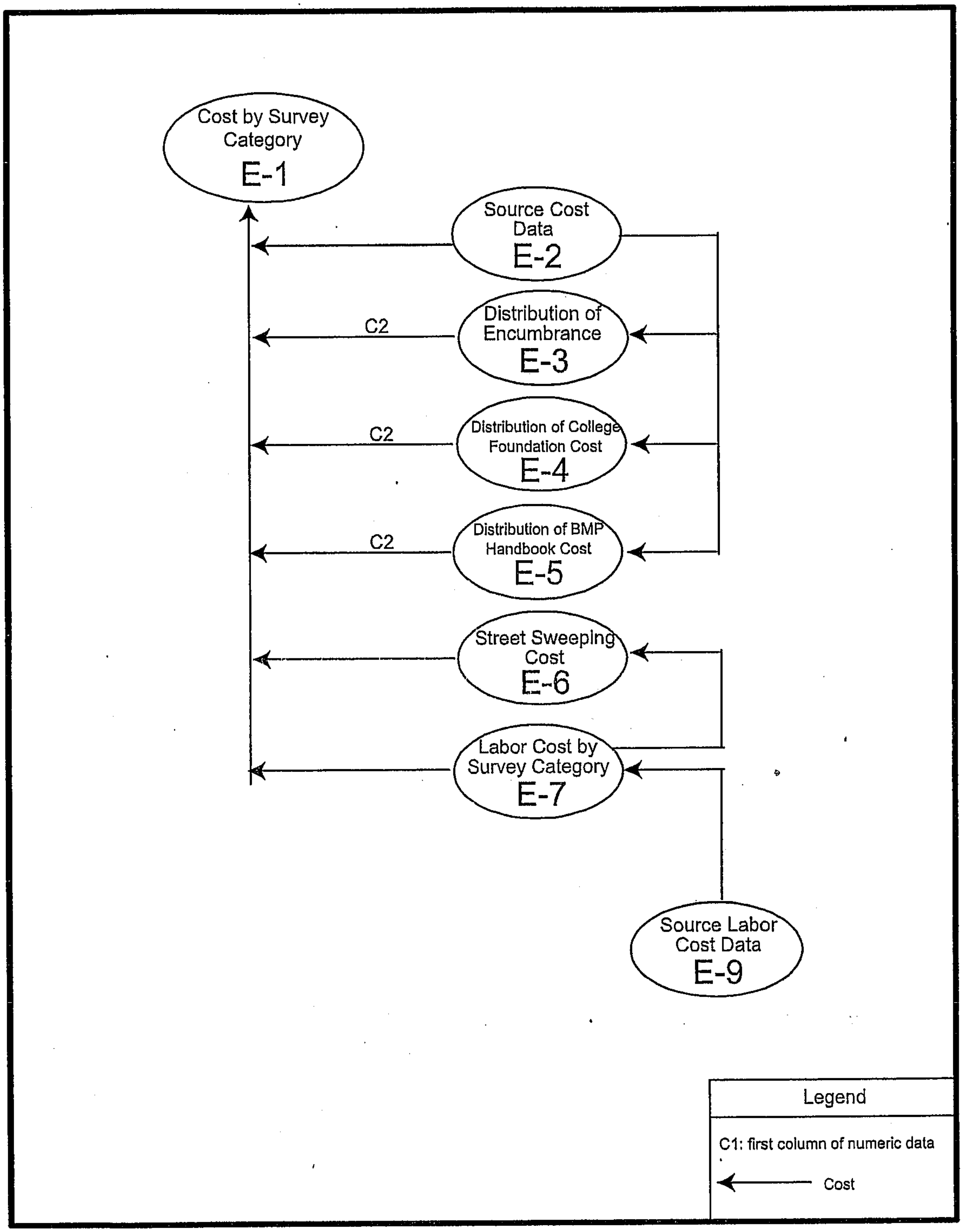


**Figure E-1. Sacramento Flowchart**



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### Illicit Discharge Detection and Elimination (IDDE)

The total cost for this category was $37,507. Labor cost is the only cost allocated to this category. Activities performed included issuance of 55 enforcement actions and investigation of all 83 calls received involving suspected illicit discharge (Sacramento, 2003b).

### Industrial and Commercial Management Programs

The total cost for this category was $42,318. Approximately 94 percent of the cost was for stormwater staff labor. The other identified cost was for developing BMP handbooks (one time annual cost, but may occur at a time later than one year). Other activities included issuance of 41 enforcement actions, development of BMP brochures for the auto body, auto washing, and auto repair industry, and creation of a Clean Water Business Partner program for the mobile pressure washing industry (Sacramento, 2003b).

### Overall Stormwater Program Management

The total cost for this category was $281,501. Activities in this program were as follows:

- Office products
- Planning
- Annual reporting
- CASQA membership fees
- Mailing
- NPDES fees
- Legal fees
- Miscellaneous
- Stormwater staff labor

### Pollution Prevention and Good Housekeeping for Municipal Operations

The total cost for this category was $3,270,806. Most of the cost for this category was for the activities of street sweeping (40 percent), drainage system maintenance (46 percent), and pump station cleaning (13 percent).

Street sweeping costs were also estimated by city staff. Street sweeping cost was estimated at $1.6 million. Street sweeping costs included the cost of sweeping 3 percent of the core downtown area 7 extra times a month which is beyond the city's permit requirement (Busath, pers. comm., 11/21/04). Due to this an annual required compliance cost was calculated for the city based on the $1.6 million estimate and permit required street sweeping frequencies (Table E-7). The calculated annual required compliance cost was $1,322,748.

Sump, drain inlet, manhole, and drain line and channel cleaning performed by city staff was reported under the Field Services labor category in Table E-8. Equipment costs for this effort was not available, but was roughly estimated as 75 percent of the labor costs as a result of consultation with city staff. This brings the total cost for drainage system maintenance to $1,514,926.

Lastly, $2,500 was attributable to this category for development of BMP handbooks (one time cost, but may occur less frequent than annually due to updates). The city also performed inspection and maintenance of parking lots (Sacramento, 2003b).

Due to inaccurate use of labor codes by city personnel for pump station cleaning, these costs were estimated by the city of Sacramento staff rather than relying on accounting record reports (Busath, pers. comm., 11/21/03). The reported labor cost of $22,552 from Table E-8 was not used in this report. Pump station cleaning, including equipment costs, was estimated at $420,000 (Busath, pers. comm., 1/11/05).

### *Post Construction Stormwater Management in New Development and Redevelopment*

The total cost of this category was $38,517. The labor costs for this category were broken down in the same way as the Construction Site Stormwater Runoff Control category. There was also cost identified for development of BMP handbooks (one time annual cost, but may occur at a time later than one year)

### *Public Education, Outreach, Involvement, and Participation*

The total cost of this category was $361,440. The costs associated with this category were for the following activities:

- Developing Integrated Pest Management (IPM)
- Television
- Radio
- Billboard
- Newspaper
- Mailings
- Participation in public events
- Water Education Foundation grant
- Project development
- Agriculture outreach
- Pet outreach
- Elementary education

- Student intern labor
- Stormwater staff labor
- University grant

Where activity statistics were available, normalized costs were calculated. Activity statistics were not available for each activity. Therefore, normalization based on total cost was not possible.

### Water Quality Monitoring

The total cost of this category was $494,577. Modeling and data analysis accounted for $131,688. Sample collection and lab cost was $303,077 and stormwater staff and student labor cost was $59,812.

### Watershed Management

The total cost of this category was $31,591, which was primarily for stormwater staff labor.

### References

City of Sacramento. 2003. "Stormwater Management Program 2002/2003 Annual Report"

## Table E - 1. Sacramento Costs Organized by Cost Survey Category

Cost Survey Categories

*Activity Description*

### Construction Site Stormwater Runoff Control

| Description | External Contract | Relation to Permit[a] | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| Overall Program | | | | | | | | | | |
| *College Foundation costs* | | New | 12,475.20 | Table E-4 | 4.8% | | | | | |
| *BMP handbooks (CASQA)* | | New | 2,500.00 | Table E-5 | 1.0% | | | | | |
| *Other constuction element* | | New | 64,778.39 | Table E-7, Item 1 | 24.8% | | | | | |
| *Construction inpections* | | New | 181,962.17 | Table E-7, Item 2 | 69.5% | 6,375 | inspections | Sacramento, 2003b | 28.54 | $/inspection |
| Total | | | 261,715.76 | | 5.4% | of total stormwater cost | | | | |
| Overall Cost Category Normalizations | | | | | | | | | | |
| total category $ per inspection | | | | | | 6,375 | inspections | Sacramento, 2003b | 41.05 | $/inspection |
| total category $ per active construction site | | | | | | 417 | active construction sites | Sacramento, 2003b | 627.62 | $/active construction site |

### Illicit Discharge Detection and Elimination

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Illegal discharge inspection* | | New | 13,816.15 | Table E-7, Item 8 | 36.8% | | | | | |
| *Other illegal discharge* | | New | 23,690.64 | Table E-7, Item 7 | 63.2% | | | | | |
| Total | | | 37,506.79 | | 0.8% | of total stormwater cost | | | | |

### Industrial and Commercial Management Programs

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *BMP Handbooks (CASQA)* | | New | 2,500.00 | Table E-5 | 5.9% | | | | | |
| *Industrial inspections* | | New | 1,823.89 | Table E-7, Item 6 | 4.3% | 39 | inspections | Sacramento, 2003b | 46.77 | $/inspection |
| *Other industrial* | | New | 37,993.92 | Table E-7, Item 5 | 89.8% | | | | | |
| Total | | | 42,317.81 | | 0.9% | of total stormwater cost | | | | |

### Overall Stormwater Program Management

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Planning-Bill Crooks* | x | New | 13,550.00 | Table E-2, Item 38 | 4.8% | | | | | |
| *NPDES fee* | | New | 10,000.00 | Table E-2, Item 40 | 3.6% | | | | | |
| *Legal Fees* | x | New | 29,585.00 | Table E-2, Item 43 | 10.5% | | | | | |
| *Federal Express* | | New | 110.00 | Table E-2, Item 44 | 0.0% | | | | | |
| *Legal Fees* | x | New | 915.00 | Table E-2, Item 45 | 0.3% | | | | | |
| *Petty cash* | | New | 1,527.00 | Table E-2, Item 48 | 0.5% | | | | | |
| *Viking office products* | | New | 324.00 | Table E-2, Item 51 | 0.1% | | | | | |
| *Annual Reporting-Wendy Alexander* | x | New | 2,480.00 | Table E-2, Item 54 | 0.9% | | | | | |
| *CASQA* | | New | 5,000.00 | Table E-2, Item 55 | 1.8% | | | | | |
| *Miscellaneous expenses* | | New | 1,108.00 | Table E-2, Item 56 | 0.4% | | | | | |
| *General stormwater activiites* | | New | 52,696.90 | Table E-7, Item 3 | 18.7% | | | | | |
| *Program management* | | New | 160,161.19 | Table E-7, Item 28 | 56.9% | | | | | |
| *Program management* | | New | 4,044.41 | Table E-7, Item 29 | 1.4% | | | | | |
| Total | | | 281,501.50 | | 5.8% | of total stormwater cost | | | | |

Table E-1 continued

### Pollution Prevention and Good Housekeeping for Municipal Operations

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Pump stations* | | Enhanced | 420,000.00 | Busath, 2004 | 12.8% | | includes equipment and labor | Busath, pers. comm., 1/12/05 | | |
| *Street sweeping* | | Enhanced | 1,322,748.02 | Table E-6 | 40.4% | 26,450 | adjusted curb miles swept | Table E-6 | 50.01 | $/curb mile swept |
| *BMP handbooks (CASQA)* | | New | 2,500.00 | Table E-5 | 0.1% | | | | | |



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## Table E – 1. Continued

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Field services (drainage system maintenance)* | | Enhanced | 865,672.17 | Table E-7 | 26.5% | | equipment estimated below | Busath, pers. comm., 1/12/05 | | |
| *Water waste activities* | | New | 896.73 | Table E-7, Item 27 | 0.0% | | | | | |
| *Other municipal operations* | | New | 9,735.09 | Table E-7, Item 15 | 0.3% | | | | | |
| *Equipment (drainage system maintenance)* | | Enhanced | 649,254.13 | Busath, 2004 | 19.8% | | calculated as 75% of field services | Busath, pers. comm., 1/12/05 | | (no backup available) |
| Total | | | 3,270,806.13 | | 67.9% | of total stormwater cost | | | | |

### Post Construction Stormwater Management in New Development and Redevelopment

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *New development* | | New | 29,779.10 | Table E-7, Item 4 | 77.3% | | | | | |
| *College Foundation costs* | | New | 6,237.60 | Table E-4 | 16.2% | | | | | |
| *BMP handbooks (CASQA)* | | New | 2,500.00 | Table E-5 | 6.5% | | | | | |
| Total | | | 38,516.70 | | 0.8% | of total stormwater cost | | | | |

### Public Education, Outreach, Involvement, and Participation

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Develop IPM* | x | New | 4,710.00 | Table E-2, Item 9 | 1.3% | | | | | |
| *Develop IPM* | x | New | 34,812.00 | Table E-2, Item 11 | 9.6% | | | | | |
| *Develop IPM* | x | New | 577.00 | Table E-2, Item 12 | 0.2% | | | | | |
| *Television* | | | | | | 201 | days | Sacramento, 2003b | 331.79 | subtotal $/day |
| *Univsion 19* | x | New | 13,010.00 | Table E-2, Item 19 | 3.6% | | | | | |
| *Comcast* | x | New | 26,284.00 | Table E-2, Item 4 | 7.3% | | | | | |
| *KCRA* | x | New | 24,000.00 | Table E-2, Item 6 | 6.6% | | | | | |
| *KXTV* | x | New | 3,396.00 | Table E-2, Item 8 | 0.9% | | | | | |
| *Radio* | | | | | | 64 | days | Sacramento, 2003b | 92.25 | subtotal $/day |
| *Clear Channel* | x | New | 4,374.00 | Table E-2, Item 3 | 1.2% | | | | | |
| *KSSJ* | x | New | 1,530.00 | Table E-2, Item 7 | 0.4% | | | | | |
| *Billboards,* | | | | | | 1 | days | Sacramento, 2003b | 5,208.00 | subtotal $/day |
| *Sign Effects* | x | New | 2,578.00 | Table E-2, Item 16 | 0.7% | | | | | |
| *Brownies* | x | New | 2,630.00 | Table E-2, Item 39 | 0.7% | | | | | |
| *Newspaper* | | | | | | 34 | days | Sacramento, 2003b | 601.32 | subtotal $/day |
| *Sac Bee* | x | New | 736.00 | Table E-2, Item 13 | 0.2% | | | | | |
| *Z.C. Optimal Solutions* | x | New | 18,781.00 | Table E-2, Item 22 | 5.2% | | | | | |
| *Sacramento Business Journal* | x | New | 928.00 | Table E-2, Item 23 | 0.3% | | | | | |
| *Mailing* | | | | | | 34,488 | impressions | Sacramento, 2003b | 0.06 | subtotal $/impression |
| *Vitali-gage Communic* | x | New | 1,522.00 | Table E-2, Item 21 | 0.4% | | | | | |
| *Auto Mailing* | | New | 653.00 | Table E-2, Item 37 | 0.2% | | | | | |
| *Public Event Participation* | | | | | | | | | | |
| *Pacific Rim* | | New | 100.00 | Table E-2, Item 1 | 0.0% | | | | | |
| *Sac Zoo* | | New | 7,000.00 | Table E-2, Item 15 | 1.9% | | | | | |
| *Other Activities* | | | | | | | | | | |
| *Wayne Neilsen* | x | New | 1,717.00 | Table E-2, Item 52 | 0.5% | | | | | |
| *Jack Nadel* | x | New | 10,406.00 | Table E-2, Item 5 | 2.9% | | | | | |
| *Safe Designs* | x | New | 764.00 | Table E-2, Item 49 | 0.2% | | | | | |
| *Water ED Found Grant* | | | | | | | | | | |
| *Water Edu Found* | | New | 2,500.00 | Table E-2, Item 18 | 0.7% | | | | | |
| *Grant* | | New | 2,500.00 | Table E-2, Item 10 | 0.7% | | | | | |
| *Project Development* | | | | | | | | | | |
| *David John Darold* | x | New | 1,756.00 | Table E-2, Item 42 | 0.5% | | | | | |
| *Lee Pitt* | x | New | 419.00 | Table E-2, Item 46 | 0.1% | | | | | |
| *Linda Taylor* | x | New | 43.00 | Table E-2, Item 47 | 0.0% | | | | | |
| *ATV video Center* | x | New | 387.00 | Table E-2, Item 2 | 0.1% | | | | | |
| *UC Regents* | x | New | 3,589.00 | Table E-2, Item 17 | 1.0% | | | | | |
| *Misc encumbrance* | | New | 15,500.00 | Table E-3 | 4.3% | | | | | |

## Table E – 1. Continued.

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Urban creeks* | | New | 750.00 | Table E-2, Item 20 | 0.2% | | | | | |
| *Agriculture outreach (cures)* | | New | 2,639.00 | Table E-2, Item 34 | 0.7% | | | | | |
| *Pet outreach (doggie bags)* | | New | 4,149.00 | Table E-2, Item 35 | 1.1% | | | | | |
| *Elementary Education (sac theatre co)* | | New | 5,100.00 | Table E-2, Item 14 | 1.4% | | | | | |
| *Public education* | | New | 93,986.89 | Table E-7, Item 9 | 26.0% | | | | | |
| *School outreach* | | New | 23,465.49 | Table E-7, Item 10 | 6.5% | | | | | |
| *Landscape grant* | | New | 6,676.64 | Table E-7, Item 12 | 1.8% | | | | | |
| *Clean Water Business Partnership* | | New | 2,279.54 | Table E-7, Item 13 | 0.6% | | | | | |
| *Grants to agencies within city jurisdiction* | | New | 2,500.00 | Table E-2, Item 41 | 0.7% | | | | | |
| *Storm drain stenciling program* | | New | 1,503.76 | Table E-7, Item 11 | 0.4% | | | | | |
| *College Foundation costs* | | New | 31,188.00 | Table E-4 | 8.6% | | | | | |
| Total | | | 361,440.32 | | 7.5% | of total stormwater cost | | | | |

Table E-1 continued

### Water Quality Monitoring

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Modeling and Data Analysis* | | | | | | | | | | |
| *Kathy Russick* | x | New | 76,017.00 | Table E-2, Item 27 | 15.4% | | | | | |
| *LWA* | x | New | 43,748.00 | Table E-2, Item 29 | 8.8% | | | | | |
| *Geosyntec* | x | New | 4,690.00 | Table E-2, Item 32 | 0.9% | | | | | |
| *CSUS foundation* | | New | 7,233.00 | Table E-2, Item 31 | 1.5% | | | | | |
| *Implementation: Sample Collection and Lab Analysis* | | | | | | | | | | |
| *Aerospeed* | x | New | 167.70 | Table E-2, Item 24 | 0.0% | | | | | |
| *Caltest* | x | New | 37,197.00 | Table E-2, Item 25 | 7.5% | | | | | |
| *County* | x | New | 247,274.00 | Table E-2, Item 26 | 50.0% | | | | | |
| *Kinetic Labs* | x | New | 2,938.00 | Table E-2, Item 28 | 0.6% | | | | | |
| *Project Development* | | New | 15,500.00 | Table E-3 | 3.1% | | | | | |
| *General monitoring* | | New | 27,291.38 | Table E-7, Item 19 | 5.5% | | | | | |
| *NPDES compliance monitoring* | | New | 9,525.69 | Table E-7, Item 20 | 1.9% | | | | | |
| *BMP effectiveness monitoring* | | New | 341.74 | Table E-7, Item 21 | 0.1% | | | | | |
| *Special monitoring studies* | | New | 409.30 | Table E-7, Item 22 | 0.1% | | | | | |
| *Coordinated monitoring program* | | New | 390.75 | Table E-7, Item 23 | 0.1% | | | | | |
| *Coordinated monitoring program* | | New | 368.56 | Table E-7, Item 24 | 0.1% | | | | | |
| *Coordinated monitoring program* | | New | 617.52 | Table E-7, Item 25 | 0.1% | | | | | |
| *Coordinated monitoring program* | | New | 8,392.24 | Table E-7, Item 26 | 1.7% | | | | | |
| *College Foundation costs* | | New | 12,475.20 | Table E-4 | 2.5% | | | | | |
| Total | | | 494,577.08 | | 10.3% | of total stormwater cost | | | | |

### Watershed Management

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Acchibald and Wallberg* | x | New | 9,595.00 | Table E-2, Item 33 | 30.4% | | | | | |
| *Brake Pad Patnership* | | New | 2,500.00 | Table E-2, Item 36 | 7.9% | | | | | |
| *Watershed stewardship* | | New | 5,565.92 | Table E-7, Item 14 | 17.6% | | | | | |
| *Target pollutant* | | New | 13,930.08 | Table E-7, Item 18 | 44.1% | | | | | |
| Total | | | 31,591.00 | | 0.7% | of total stormwater cost | | | | |

Total Stormwater Costs 4,819,973.09

a. This column indicates whether required activities were being performed prior to stormwater permits. In some cases activities were enhanced due to permit requirements.

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Table E-2. Source Data Table Submitted by City of Sacramento (cost survey categories added)

| Item # | City of Sacramento Category | Cost | Cost Survey Category[1] |
|---|---|---|---|
| | **Public Outreach** | | |
| 1 | Pacific Rim | 100 | Public Education |
| 2 | ATV video Center | 387 | Public Education |
| 3 | Clear Channel | 4,374 | Public Education |
| 4 | Comcast | 26,284 | Public Education |
| 5 | Jack Nadel | 10,406 | Public Education |
| 6 | KCRA | 24,000 | Public Education |
| 7 | KSSJ | 1,530 | Public Education |
| 8 | KXTV | 3,396 | Public Education |
| 9 | Mark McCarthy | 4,710 | Public Education |
| 10 | Grant | 2,500 | Public Education |
| 11 | Ogilvy | 34,812 | Public Education |
| 12 | Rooney Design | 577 | Public Education |
| 13 | Sac Bee | 736 | Public Education |
| 14 | Sac Theater Co | 5,100 | Public Education |
| 15 | Sac Zoo | 7,000 | Public Education |
| 16 | Sign Effects | 2,578 | Public Education |
| 17 | UC Regents | 3,589 | Public Education |
| 18 | Water Edu Found | 2,500 | Public Education |
| 19 | Univision 19 | 13,010 | Public Education |
| 20 | Urban Creeks | 750 | Public Education |
| 21 | Vitali-gage Communic | 1,522 | Public Education |
| 22 | Z.C. Optimal Solutions | 18,781 | Public Education |
| 23 | Sac Business Jour | 928 | Public Education |
| | **Monitoring** | | |
| 24 | Aerospeed | 168 | Monitoring |
| 25 | Caltest | 37,197 | Monitoring |
| 26 | County | 247,274 | Monitoring |
| 27 | Kathy Russick | 76,017 | Monitoring |
| 28 | Kinetic Labs | 2,938 | Monitoring |
| 29 | LWA | 43,748 | Monitoring |
| 30 | Sequoia Analytical | 0 | |
| 31 | CSUS foundation | 7,233 | Monitoring |
| 32 | Geosyntec | 4,690 | Monitoring |

**Table E-2. Continued.**

| | | | |
|---|---|---|---|
| | **Target Pollutant** | | |
| 33 | Acchibald and Wallberg | 9,595 | Watershed |
| 34 | Cures | 2,639 | Public Education |
| 35 | Doggie Bags | 4,149 | Public Education |
| 36 | Brake Pad Patnership | 2,500 | Watershed |
| | **Misc** | | |
| 37 | Auto Mailing | 653 | Public Education |
| 38 | Bill Crooks | 13,550 | Management |
| 39 | Brownies | 2,630 | Public Education |
| 40 | NPDES fee | 10,000 | Management |
| 41 | CSUS | 2,500 | Public Education |
| 42 | David John Darold | 1,756 | Public Education |
| 43 | Downey Brand | 29,585 | Management |
| 44 | Fedex | 110 | Management |
| 45 | George & Shapiro | 915 | Management |
| 46 | Lee Pitt | 419 | Public Education |
| 47 | Linda Taylor | 43 | Public Education |
| 48 | Petty cash | 1,527 | Management |
| 49 | Safe Designs | 764 | Public Education |
| 50 | BMP handbooks | 10,000 | See Table E-5 |
| 51 | Viking Office Prods | 324 | Management |
| 52 | Wayne Neilsen | 1,717 | Public Education |
| 53 | Misc encumbrance | 31,000 | See Table E-3 |
| 54 | Wendy Alexander | 2,480 | Management |
| 55 | CASQA | 5,000 | Management |
| 56 | Misc Expenses | 1,108 | Management |
| | **Students** | | |
| 57 | College Foundation | 62,376 | See Table E-4 |
| | Total | 786,175 | |

(Source: Busath, pers. comm., 11/21/03)

1. Cost Categories Abbreviated According to the Following:
   - Construction: Construction Site Stormwater Runoff Control
   - Illicit Discharge: Illicit Discharge Detection and Elimination
   - Industrial: Industrial and Commercial Management Programs
   - Management: Overall Stormwater Program Management
   - Pollution Prevention: Pollution Prevention and Good Housekeeping for Municipal Operations
   - Post Construction: Post Construction Water Management in New Development and Redevelopment
   - Public Education: Public Education, Outreach, Involvement, and Participation
   - Monitoring: Water Quality Monitoring
   - Watershed: Watershed Management

### Table E-3. Distribution of Miscellaneous Encumbrance Between Public Education and Monitoring

| Cost | Source | Percent Allocation | Category | Reference | Allocated Cost |
|---|---|---|---|---|---|
| 31,000.00 | Table 2, Item 53 | 50% | Public Education | Busath, pers. comm., 1/22/04 | 15,500.00 |
| 31,000.00 | Table 2, Item 53 | 50% | Monitoring | Busath, pers. comm., 1/22/04 | 15,500.00 |
| Total | | 100% | | | 31,000.00 |

### Table E-4. Distribution of College Foundation Costs for Student Internship Program

| Cost | Source | Percent Allocation | Category | Reference | Allocated Cost |
|---|---|---|---|---|---|
| 62,376.00 | Table E-2, Item 57 | 50% | Public Education | Busath, pers. comm., 1/22/04 | 31,188.00 |
| 62,376.00 | Table E-2, Item 57 | 20% | Construction | Busath, pers. comm., 1/22/04 | 12,475.20 |
| 62,376.00 | Table E-2, Item 57 | 20% | Monitoring | Busath, pers. comm., 1/22/04 | 12,475.20 |
| 62,376.00 | Table E-2, Item 57 | 10% | Post Construction | Busath, pers. comm., 1/22/04 | 6,237.60 |
| Total | | 100% | | | 62,376.00 |

### Table E-5. Distribution of BMP Handbooks (CASQA) between Industrial, Municipal, New Development, and Construction

| Cost | Source | Percent Allocation | Category | Reference | Allocated Cost |
|---|---|---|---|---|---|
| 10,000.00 | Table E-2, Item 50 | 25% | Industrial/Commercial | Busath, pers. comm., 1/22/04 | 2,500.00 |
| 10,000.00 | Table E-2, Item 50 | 25% | Municipal | Busath, pers. comm, 1/22/04 | 2,500.00 |
| 10,000.00 | Table E-2, Item 50 | 25% | Post Construction | Busath, pers. comm, 1/22/04 | 2,500.00 |
| 10,000.00 | Table E-2, Item 50 | 25% | Construction | Busath, pers. comm, 1/22/04 | 2,500.00 |
| Total | | 100% | | | 10,000.00 |

### Table E-6. Calculation of Street Sweeping Cost

| Description | Dollar Amount of Statistic | Reference |
|---|---|---|
| Actual Cost | 1,600,000.00 | Busath, pers. comm., 1/22/04 |
| monthly req. miles | 2,200 | Sacramento, 2003b |
| 6/year req. miles | 0 | Sacramento, 2003b |
| 1/year req. miles | 50 | Sacramento, 2003b |
| annual required | 26,450 | Calculation |
| monthly actual est. mi. | 2,662 | Busath, pers. comm., 1/22/04 |
| 6/year actual est. mi. | 0 | Sacramento, 2003b |
| 1/year actual est. mi. | 50 | Sacramento, 2003b |
| annual actual est. mi. | 31,994 | Calculation |
| annual req. cost est. | 1,322,748.02 | Calculation |

Table E-7. Labor Allocations for Sacramento Categories with Corresponding Cost Survey Categories

| Item # | Sacramento Category | City Labor Code | Labor Cost | Cost Survey Category |
|---|---|---|---|---|
| 1 | Construction Element | HA | 64,778.39 | Construction |
| 2 | Construction Inspections | HA1 | 181,962.17 | Construction |
| 3 | General Stormwater Actvities | HAA | 52,696.90 | Management |
| 4 | New Development Element | HB | 29,779.10 | Post Construction |
| 5 | Industrial Element | HC | 37,993.92 | Industrial |
| 6 | Industrial Inspection | HC1 | 1,823.89 | Industrial |
| 7 | Illegal Discharge Program | HD | 23,690.64 | Illicit Discharge |
| 8 | Illegal Discharge Inspection | HD1 | 13,816.15 | Illicit Discharge |
| 9 | Public Education Program | HE | 93,986.89 | Public Education |
| 10 | School Outreach Program | HE1 | 23,465.49 | Public Education |
| 11 | Stormdrain Stenciling Program | HE2 | 1,503.76 | Public Education |
| 12 | NN Landscape Grant | HE3 | 6,676.64 | Public Education |
| 13 | CWBP | HE4 | 2,279.54 | Public Education |
| 14 | Watershed Stewardship | HF | 5,565.92 | Watershed |
| 15 | Municipal Operations | HG | 9,735.09 | Pollution Prevention |
| 16 | Plant Services Stormwater Activities | HH | 22,552.19 | See Table E-1, pump stations |
| 17 | Field Services Stormwater Activities | HI | 865,672.17 | Pollution Prevention |
| 18 | Target Pollutant | HJ | 13,930.08 | Watershed |
| 19 | Monitoring | HK | 27,291.38 | Monitoring |
| 20 | NPDES Compliance Monitoring | HK1 | 9,525.69 | Monitoring |
| 21 | BMP Effectiveness Monitoring | HK2 | 341.74 | Monitoring |
| 22 | Special Monitoring Studies | HK3 | 409.30 | Monitoring |
| 23 | Coordinated Monitoring Program | HK4 | 390.75 | Monitoring |
| 24 | Coordinated Monitoring Program | HK5 | 368.56 | Monitoring |
| 25 | Coordinated Monitoring Program | HK6 | 617.52 | Monitoring |
| 26 | Coordinated Monitoring Program | HK7 | 8,392.24 | Monitoring |
| 27 | Water Waste Activities | HL | 896.73 | Pollution Prevention |
| 28 | Program Management | HM | 160,161.19 | Management |
| 29 | Program Management | PM | 4,044.41 | Management |
| | Total | | 1,664,348.44 | |

(Source: Table E-8)



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**Table E-8. Labor Cost Data as Submitted by City of Sacramento Staff**

City of Sacramento
Department of Utilities
Project Accounting Management System (PAMS)

| Job # | Description | Org | Rept Catg | Total Employee Expense | Indiv Hourly Expense |
|---|---|---|---|---|---|
| 21233 | NPDES PROGRAM | 3322 | HH | 665.49 | 95.1 |
| | | 3323 | HH | 4,122.06 | 64.4 |
| | | | HH | 1,410.18 | 58.8 |
| | | | HH | 3,508.67 | 48.7 |
| | | | HH | 1,944.98 | 44.2 |
| | | | HH | 1,766.04 | 31.5 |
| | | | HH | 1,124.38 | 70.3 |
| | | | HA1 | 108,293.85 | 63.9 |
| | | | HH | 868.3 | 64.3 |
| | | | HH | 1,023.82 | 64 |
| | | | HH | 930.52 | 58.2 |
| | | | HH | 198.42 | 49.6 |
| | | | HH | 448.59 | 64.1 |
| | | | HH | 384.49 | 64.1 |
| | | | HH | 656.76 | 41 |
| | | | HH | 283.2 | 35.4 |
| | | | HH | 1,122.86 | 70.2 |
| | | 3331 | HH | 2,009.09 | 24.8 |
| | | | HH | 84.34 | 42.2 |
| | | | HA | 2,371.26 | 25.9 |
| | | | HA1 | 6,658.08 | 26.4 |
| | | | HAA | 2,949.16 | 26.4 |
| | | | HAA | 1,463.31 | 41.8 |
| | | | HD | 49.61 | 24.8 |
| | | | HE | 655.9 | 25.7 |
| | | | HE1 | 1,916.75 | 26.1 |
| | | | HE2 | 417.95 | 26.1 |
| | | | HF | 99.23 | 24.8 |
| | | | HK | 244.3 | 27.1 |
| | | | HK3 | 198.43 | 24.8 |
| | | 3332 | HAA | 6,475.21 | 89.9 |
| | | | HE | 2,116.34 | 90.1 |
| | | | HE1 | 1,461.61 | 89.5 |
| | | | HG | 8,302.14 | 90.2 |
| | | | HJ | 11,187.93 | 89.6 |

**Table E-8. Continued.**

| | | | | |
|---|---|---|---|---|
| | | HK | 17,265.87 | 89.4 |
| | | HK1 | 4,597.83 | 89 |
| | | HK2 | 162.9 | 89 |
| | | HK4 | 266.5 | 88.8 |
| | 3333 | HK5 | 368.56 | 0 |
| | | HK6 | 617.52 | 65 |
| | | HK7 | 8,392.24 | 88.8 |
| 21233 NPDES PROGRAM | 3333 | HA | 7,712.62 | 61.2 |
| | | HA | 52,918.39 | 89 |
| | | HA | 1,776.12 | 44.4 |
| | | HA1 | 5,602.74 | 62.3 |
| | | HA1 | 61,407.50 | 43.6 |
| | | HAA | 12,504.88 | 61.9 |
| | | HAA | 13,331.24 | 66.7 |
| | | HAA | 12,627.60 | 89.2 |
| | | HAA | 3,345.50 | 65 |
| | | HB | 4,303.02 | 62.4 |
| | | HB | 25,476.08 | 88.5 |
| | | HC | 1,745.21 | 62.3 |
| | | HC | 35,847.63 | 66.5 |
| | | HC | 401.08 | 89.1 |
| | | HC1 | 248.44 | 62.1 |
| | | HC1 | 1,575.45 | 65.6 |
| | | HD | 23,193.44 | 66.6 |
| | | HD | 447.59 | 89.5 |
| | | HD1 | 13,816.15 | 68.2 |
| | | HE | 11,310.88 | 62.3 |
| | | HE | 156.04 | 62.4 |
| | | HE | 928.86 | 88.5 |
| | | HE | 78,818.87 | 69.4 |
| | | HE1 | 4,083.84 | 67.5 |
| | | HE1 | 4,279.00 | 89.1 |
| | | HE1 | 11,724.29 | 67.6 |
| | | HE2 | 1,085.81 | 67.9 |
| | | HE3 | 6,676.64 | 65.5 |
| | | HE4 | 2,279.54 | 67.4 |
| | | HF | 62.43 | 62.4 |
| | | HF | 987.49 | 89.8 |
| | | HF | 4,416.77 | 63.1 |
| | | HG | 1,164.59 | 68.5 |
| | | HG | 268.36 | 89.5 |
| | | HJ | 1,133.19 | 100.7 |
| | | HJ | 1,608.96 | 67 |
| | | HK | 804.75 | 100.6 |
| | | HK | 1,499.54 | 68.2 |
| | | HK | 7,266.64 | 89.2 |

**Table E-8. Continued.**

| | | | | |
|---|---|---|---|---|
| | | HK | 210.28 | 70.1 |
| | | HK1 | 4,927.86 | 55.7 |
| | | HK2 | 178.84 | 89.4 |
| 21233 NPDES PROGRAM | 3333 | HK3 | 210.87 | 38.3 |
| | | HK4 | 124.25 | 62.1 |
| | | HL | 800.31 | 66.7 |
| | | HL | 96.42 | 48.2 |
| | | HM | 160,070.30 | 100.4 |
| | | HM | 90.89 | 29.5 |
| | | PM | 4,044.41 | 101.1 |
| | 3342 | HI | 1,440.10 | 53.3 |
| | 3343 | HI | 2,252.63 | 56.3 |
| | | HI | 205.78 | 51.4 |
| | | HI | 16,387.75 | 46.6 |
| | | HI | 29,009.49 | 45.6 |
| | | HI | 53,108.99 | 54.6 |
| | | HI | 945.65 | 43 |
| | | HI | 2,059.16 | 51.5 |
| | | HI | 1,486.70 | 41.3 |
| | | HI | 46,709.55 | 50 |
| | | HI | 60,251.76 | 55.9 |
| | | HI | 421.01 | 52.6 |
| | | HI | 23,368.00 | 44.3 |
| | | HI | 11,685.67 | 46.6 |
| | | HI | 24,722.55 | 44 |
| | | HI | 1,420.81 | 52.6 |
| | | HI | 1,197.95 | 33.3 |
| | | HI | 33,694.50 | 48.8 |
| | | HI | 25,045.38 | 42.7 |
| | | HI | 12,318.28 | 50.3 |
| | | HI | 15,905.71 | 44.8 |
| | | HI | 28,123.15 | 56 |
| | | HI | 43,011.80 | 55.8 |
| | | HI | 77,791.72 | 49.9 |
| | | HI | 6,085.05 | 56.9 |
| | | HI | 89,605.65 | 62.8 |
| | | HI | 84,737.98 | 55.3 |
| | | HI | 2,041.63 | 51 |
| | | HI | 4,134.41 | 51.7 |
| | | HI | 61,389.23 | 40.7 |
| | | HI | 510.55 | 63.8 |
| | | HI | 22,888.86 | 48.5 |
| | | HI | 1,291.63 | 47.8 |
| | | HI | 80,423.09 | 54.1 |
| | | Total | 1664348.44 | 59.92 |

(Source: Busath, pers. comm., 11/21/03)

The backup calculations for the cost for each cost survey category in Section 8 and the sources of the cost data are presented in this appendix. Tables are generally presented by sequentially increasing levels of detail. Figure F-1 illustrates how data is shared throughout the tables.

Table F-1 contains all costs organized into the various standard cost survey categories. The subtotals for each cost category are also presented in Section 8, Table 8-2. The remaining tables (F-2 through F-7) present the detailed back-up information for the numbers in Table F-1. Table F-1 is linked to the back-up tables by the table and item numbers in the 'Source' column. Most of the cost information provided by city staff is listed in Table F-2. Item numbers corresponding to the subtotals in Table F-2 were added to the left hand column to easily show how the numbers are pulled forward to Table F-1. The right hand column in Table F-2 was added to show how costs were allocated to the cost survey categories. Table F-1 entries that were not taken directly from Table F-2 are found in Tables F-3 through F-7.

For the city of Santa Clarita, labor costs of the stormwater staff are not distributed among the various survey categories. Instead, it is all captured under Overall Stormwater Program Management. Thus, comparing costs with other municipalities where such costs are distributed, Santa Clarita's Overall Stormwater Management Program costs will be higher.

Detailed descriptions of how the costs were developed are contained in the following paragraphs.

### *Construction Site Stormwater Runoff Control*

The total cost of this category was $74,995. The only cost attributed to this category was for inspections. The city conducted 11,746 inspections, but this number reflects multiple inspections for various construction activities at the same site (Santa Clarita, 2003b). Since this number does not solely represent stormwater inspections, this should be considered when comparing these inspection statistics with that of the other cities. Therefore, cost was normalized per active construction site (64) (Santa Clarita, 2003b). Other activities in this category included:

- Development of pollution prevention handouts directly related to specific construction functions
- The city's Environmental, Building and Safety, and Public Works inspectors completed site visits on a daily basis
- Cited contractors in the event of illicit connection detection

Santa Clarita

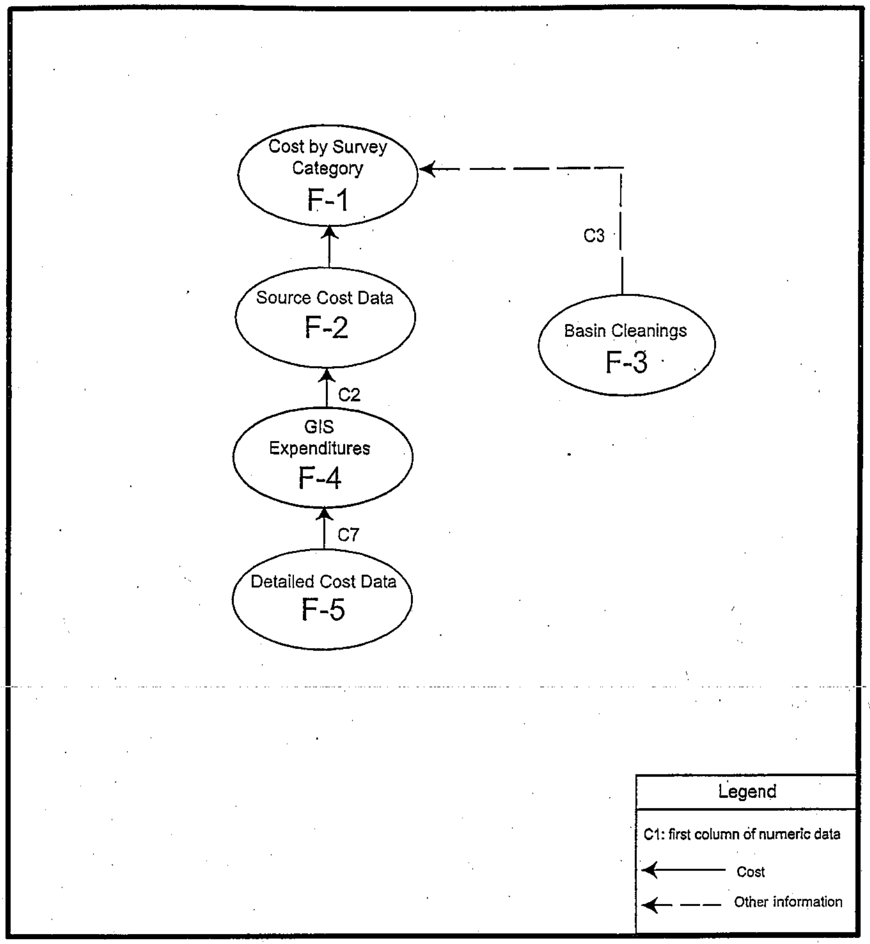


**Figure F-1. Santa Clarita Flowchart**

## *Illicit Discharge Detection and Elimination (IDDE)*

The total cost of this category was $114,831. Though the city labeled this cost as operation and maintenance activities, activities were specific to identification and elimination of illicit connections and discharges.

The Los Angeles Flood Control District (LAFCD) owns and maintains 122,354 feet of open channel all of which was screened for illicit connections during the 2002/03 fiscal year. Out of the 20 illicit connections that were identified by screening, all were investigated, terminated, removed, and resulted in enforcement action (Santa Clarita, 2003b).

Also, 349 illicit discharges were reported. Of these, 291 were discontinued/cleaned up voluntarily through enforcement and the source identified, 2 were cleaned up with no source identified, 50 resulted in no evidence of discharge, 27 were determined to be conditionally



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exempt, and 305 resulted in enforcement action. (Santa Clarita, 2003b). Normalized cost is $311 per investigation of both illicit connections and illicit discharges (20+349). This includes all associated follow up activities performed by the city as described above.

### *Industrial and Commercial Management Programs*

The total cost of this category was $12,600. The only cost for this category was for inspection of industrial and commercial facilities. The city inspection staff performed 110 inspections during 2002/03. The city of Santa Clarita contracts with Los Angeles County of perform these inspections but are done by city staff (Cramer, pers. comm., 4/22/04). Enforcement actions were issued which included 17 verbal warnings and 4 notices to comply. (Santa Clarita, 2003b).

### *Overall Stormwater Program Management*

The total cost for this category was $515,352. These costs are for administrative activities and development planning. Stormwater staff time (including overhead allocation) used to oversee or implement the activities in the other cost categories accounted for $438,832. Overhead allocation (other supporting city functions, building, etc.) was $253,073. This number is described in the footnote to Table F-2. Development planning cost was $76,520. These costs were for activities the city does to insure developers are following SUSMP[1] standards. Maintenance of the stormwater section of city's website was also performed.

### *Pollution Prevention and Good Housekeeping for Municipal Operations*

The total cost for this category was $859,754. Activities performed in this category were for catch basin cleaning, trash pick-up, and street sweeping. The cost attributed to catch basin cleaning was $251,908. During 2002/03, 1,482 catch basins were cleaned (Table F-3). The cost attributed to street sweeping was $557,443. The city sweeps all streets once a week (Santa Clarita, 2003b). A total of 900 curb miles were swept per week in 2002/03 (Cramer, pers. comm., 4/22/04). Trash pick-up costs were $50,403 for the household hazardous waste program.

### *Post Construction Stormwater Management in New Development and Redevelopment*

The adjusted cost of this category was $106,925. The total cost for this category submitted by the city of Santa Clarita was $256,950. Of the cost, $97,813 was for vehicles for catch basin cleaning (Cramer, pers. comm., 4/22/04). These capital costs were recurring for other projects at an unknown interval and were assumed to be annual for the purposes of this survey. The remaining $9,112 was for maintenance and conveyance of one detention basin (Cramer, pers. comm., 4/22/04).

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[1] SUSMP: Standard Urban Storm Water Mitigation Plans (SUSMPs) are often referenced by permits. They set treatment requirements for new construction and redevelopment. (www.swrcb.ca.gov)

### *Public Education and Outreach* and *Public Involvement and Participation*

The total cost for these categories was $49,130.. These categories were combined for the city of Santa Clarita. This cost includes employee training to administer these categories. Activities in this category included:

- Storm drain stenciling: Out of the city owned 440 drain inlets, 45 were marked with a no dumping message
- Maintained stormwater hotline: The city received approximately 30 calls per day relating to trash, household hazardous waste, and stormwater (Cramer, pers. comm., 4/22/04)
- Print, television, radio, and other media: Approximately 5 million impressions were made (for the entire permitted area). A breakdown for Santa Clarita was not available
- School outreach: An environmental mascot visited schools and public events to educate attendees on stormwater issues. Children's activity books were distributed at appearances. Flyers were distributed to promote the River Rally event
- Cooperated with the principal permittee to develop specific outreach programs to target pollutants in their area
- Distributed pollutant-specific materials
- Developed and distributed brochures and door hangers to specific residents
- Attended 4 workshop/community events to discuss stormwater pollution

Programs supported by the principal permittee were funded in part by a contribution from the city of Santa Clarita in the amount of $45,822. The remaining activities were performed by stormwater staff and that cost breakdown was not available.

### *Water Quality Monitoring*

The total cost of this category was $3,300 (Table F-2). This included monitoring for diazinon multiple times at one site (Cramer, pers. comm., 4/22/04).

### *Watershed Management*

The total cost of this category was $332,949. This cost was allocated to this category based on estimates from city staff. The staff estimated that 50 percent of GIS cost was attributable to stormwater activities (Table F-4).

### *References*

City of Santa Clarita. 2003. "Los Angeles County Municipal Storm Water Permit (Order 01-182) Individual Annual Reporting Form, Attachment U-4"

## Table F - 1. Santa Clarita Cost Organized by Cost Category

**Cost Survey Categories**

*Activity Description*

### Construction Site Stormwater Runoff Control

| Description | External Contract | Relation to Permit[a] | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Construction inspections* | | New | 74,995.00 | Table F-2, Item 9 | 100% | 64 | active construction sites | Santa Clarita, 2003b | 1,171.80 | $/active construction site |
| Total | | | 74,995.00 | | 3.6% | of total stormwater cost | | | | |

### Illicit Discharge Detection and Elimination

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Operations and maintenance* | | New | 114,831.05 | Table F-2, Item 16 | 100% | 369 | investigations | Santa Clarita, 2003b | 311.20 | $/investigation |
| Total | | | 114,831.05 | | 5.5% | of total stormwater cost | | | | |

### Industrial and Commercial Management Programs

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Industrial/Commercial site visit activities* | | New | 12,600.00 | Table F-2, Item 7 | 100% | 110 | inspections | Santa Clarita, 2003b | 114.55 | $/inspection |
| Total | | | 12,600.00 | | 0.6% | of total stormwater cost | | | | |

### Overall Stormwater Program Management

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Administrative costs* | | New | 438,832.00 | Table F-2, Item 1 | 85.2% | | | | | |
| *Development planning* | | New | 76,519.55 | Table F-2, Item 8 | 14.8% | | | | | |
| Total | | | 515,351.55 | | 24.9% | of total stormwater cost | | | | |

### Pollution Prevention and Good Housekeeping for Municipal Operations

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Catch basin cleaning* | | Enhanced | 251,907.99 | Table F-2, Item 12 | 29.3% | 1,482 | basin cleanings | Table F-3 | 169.98 | $/basin cleaning |
| *Trash pick-up* | | Existing | 50,402.55 | Table F-2, Item 13 | 5.9% | | | | | |
| *Street sweeping* | | Enhanced | 557,443.16 | Table F-2, Item 11 | 64.8% | 46,800 | curb miles swept | Cramer, pers. comm., 4/22/04 | 11.91 | $/curb mile swept |
| Total | | | 859,753.70 | | 41.5% | of total stormwater cost | | | | |

Table F – 1. Continued.

Post Construction Stormwater Management in New Development and Redevelopment

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *BMP maintenance* | | New | 9,111.93 | Table F-2, Item 10 | 8.5% | | | | | |
| *Capital costs* | | New | 97,813.00 | Table F-2, Item 14 | 91.5% | | | | | |
| Total | | | 106,924.93 | | 5.2% | of total stormwater cost | | | | |

Public Education, Outreach, Involvement, and Participation

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Public education and outreach* | | New | 45,821.98 | Table F-2, Item 3 | 93.3% | | | | | |
| *Employee training* | | New | 3,308.39 | Table F-2, Item 4 | 6.7% | | | | | |
| Total | | | 49,130.37 | | 2.4% | of total stormwater cost | | | | |

Water Quality Monitoring

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Monitoring* | | New | 3,300.00 | Table F-2, Item 18 | 100% | | | | | |
| Total | | | 3,300.00 | | 0.2% | of total stormwater cost | | | | |

Watershed Management

| Description | External Contract | Relation to Permit | Dollar Amount | Source | % of Category | Activity Statistic | Notes/Units | Reference | Normalized Cost | Notes/Units |
|---|---|---|---|---|---|---|---|---|---|---|
| *Watershed management* | | New | 332,949.00 | Table F-2, Item 19 | 100% | | | | | |
| Total | | | 332,949.00 | | 16.1% | of total stormwater cost | | | | |

Total Stormwater Costs 2,069,835.60

a. This column indicates whether required activities were being performed prior to stormwater permits. In some cases activities were enhanced due to permit requirements.

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**Table F-2. Source Data Table Submitted by City of Santa Clarita in their Annual Report Form for Los Angeles County Municipal Stormwater Permit (cost survey categories added)**

| Item # | City of Santa Clarita Category | Cost | Cost Survey Category[1] |
|---|---|---|---|
| | **Program Mangement** | | |
| 1 | Administrative Costs | 438,832.00 | [2] Management |
| 2 | Capital Costs | 0.00 | |
| | **Public Information and Participation** | | |
| 3 | Public Outreach/Education | 45,821.98 | Public Education |
| 4 | Employee Training | 3,308.39 | Public Education |
| 5 | Corporate Outreach | 0.00 | |
| 6 | Business Assistance | 0.00 | |
| 7 | Industrial/Commercial Inspection/Site Visit Actvities | 12,600.00 | Industrial |
| 8 | Development Planning | 76,519.55 | Management |
| | **Development Construction** | | |
| 9 | Construction Inspections | 74,995.00 | Construction |
| | **Public Agency Activities** | | |
| 10 | Maintenance of structural and treatment control BMPs | 9,111.93 | Post Construction |
| 11 | Municipal Street Sweeping | 557,443.16 | Pollution Prevention |
| 12 | Catch Basin Cleaning | 251,907.99 | Pollution Prevention |
| 13 | Trash Collection/Recycling | 50,402.55 | Pollution Prevention |
| 14 | Capital Costs | 97,813.00 | [3] Post Construction |
| 15 | Other | 0.00 | |
| | **IC/ID Program** | | |
| 16 | Operations and Maintenance | 114,831.05 | Illicit Discharge |
| 17 | Capital Costs | 0.00 | |
| 18 | Monitoring | 3,300.00 | Monitoring |
| 19 | Other (Watershed Management) | 332,949.00 | [4] Watershed |
| | Total | 2,069,835.60 | |

(Source: Santa Clarita 2003b)

1. Cost Categories Abbreviated According to the Following:
   - Construction: Construction Site Stormwater Runoff Control
   - Illicit Discharge: Illicit Discharge Detection and Elimination
   - Industrial: Industrial and Commercial Management Programs
   - Management: Overall Stormwater Program Management
   - Pollution Prevention: Pollution Prevention and Good Housekeeping for Municipal Operations
   - Post Construction: Post Construction Water Management in New Development and Redevelopment
   - Public Education: Public Education, Outreach, Involvement, and Participation
   - Monitoring: Water Quality Monitoring
   - Watershed: Watershed Management
2. Cost reported in the annual report form was $184,710. Per personal communication with Dan Smith, this number was adjusted up to $185,759 because of $1,049 in previously unallocated labor for stormwater staff. Another $253,073 was also added as the cost of overhead allocation. Overhead allocation was not included in the annual report and it pays for support by other departments such a payroll, human resources, etc. as well as a fraction of building costs.
3. $137,784 was adjusted down to $97,813 after a more thorough review by city finance staff. The city suggested we add $150,025 for the curb line and gutter maintenance program, but this cost could not be established as a stormwater compliance cost.
4. From Table 7-3.

**Table F-3. Calculation of Number of Basin Cleanings**

| Type | Number | Reference | Frequency (yearly) | Reference | Total Cleanings |
|---|---|---|---|---|---|
| Priority A | 65 | Santa Clarita, 2003b | 3 | Santa Clarita, 2003b | 195 |
| Priority B | 180 | Santa Clarita, 2003b | 3 | Santa Clarita, 2003b | 540 |
| Priority C | 249 | Santa Clarita, 2003b | 3 | Santa Clarita, 2003b | 747 |
| Total | 494 | | | | 1,482 |

**Table F-4. Calculation of GIS Expenditures Relating to Stormwater**

| Amount | Source | Percent Allocation | Category | Reference | Allocated Cost |
|---|---|---|---|---|---|
| 665,897.12 | Table F-5 | 50% | Watershed Management | Cramer, pers. comm., 6/9/04 | 332,948.56 |
| 665,897.12 | Table F-5 | 50% | Not Related to Stormwater | Cramer, pers. comm., 6/9/04 | 332,948.56 |
| Total | | 100% | | | 665,897.12 |



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**Table F-5. Financial Cost Data Submitted by City of Santa Clarita**

STORMWATER UTILITY FINANCIAL PROJECTIONS
Financial History

| | | 1996-97 Actuals | 1997-98 Actuals | 1998-99 Actuals | 1999-00 Actuals | 2000-01 Actuals | 2001-02 Actuals | 2002-03 Actuals |
|---|---|---|---|---|---|---|---|---|
| REVENUES: | | | | | | | | |
| | User Fee | 1,847,538 | 2,149,920 | 2,527,683 | 1,925,118 | 2,101,130 | 1,954,966 | 2,251,307 |
| | (Supplemental Refund) | | | | | | | |
| | Interest Income | 42,104 | 58,193 | 79,913 | 86,125 | 143,197 | 96,382 | 81,505 |
| | Misc. Revenues | | 103 | 1,811 | | | 103,285 | 147,464 |
| | Sale of Maps & Publications | | | 140 | 1,792 | 1,696 | 2,597 | 1,929 |
| | Operating Transfers In | | | 53,633 | 125,028 | 277,836 | 323,142 | 289,765 |
| Total Revenues | | 1,889,642 | 2,208,216 | 2,663,179 | 2,138,063 | 2,523,859 | 2,480,373 | 2,771,971 |
| OPERATING EXPENDITURES: | | | | | | | | |
| 2314 | GIS | 965,352 | 327,471 | 213,712 | 232,334 | 486,642 | 504,794 | 665,897 |
| 4311 | Stormwater Engineering | | | | 56,652 | 17,924 | | |
| 5720 | Stormwater Utility Admin | | 312,673 | 323,391 | 691,677 | 539,508 | 1,561,987 | 554,823 |
| 5740 | Stormwater Field Activities | 572,534 | 601,604 | 627,845 | 688,919 | 740,401 | 994,760 | 928,992 |
| 8140 | Stormwater Attorney Services | | | | | | | |
| | Transfers Out | | | | | | | |
| | Overhead Allocation - 11% of Rev | 197,820 | 197,820 | 197,820 | 197,820 | 197,820 | 203,895 | 253,073 |
| | Audit Adj - AR Allowance | | | | | | | |
| TOTAL OPERATING EXPENDITURES | | 1,735,706 | 1,439,567 | 1,362,768 | 1,867,401 | 1,982,295 | 3,265,435 | 2,402,785 |
| CAPITAL PROJECTS: | | | | | | | | |
| | 1996-97 Access Ramp | 0 | 18,636 | 6,364 | | | | |
| | 1997-98 Curb Gutter & Flowline | | | 115,000 | | | | |
| | 1999-00 Stormdrain Repairs | | | | | 0 | | |
| | 1999-00 Curb Gutter Flowline | | | | 157,415 | | | |
| | Storm Drain Repairs | | | (97,660) | 110,170 | 17,500 | | |
| M0031 | Annual Curb Gutter Flowline | | | | | | 151,766 | |
| M0032 | Storm Drain Transfer Program | | | | | | 73,428 | 316,215 |
| M0037 | Annual Curb Gutter Flowline | | | 190,668 | | | | 150,025 |
| | Water Discharge Retrofit | | | 16,683 | | | | |
| | Galeton Street Improvements | | | 18,850 | | | | |
| | 2000-01 Curb Gutter Flowline | | | | | 177,000 | | |
| | Annual Stormdrain Repairs | | | | | 0 | | |
| TOTAL CAPITAL PROJECTS | | 0 | 18,636 | 249,905 | 267,585 | 194,500 | 225,194 | 466,240 |
| Total Expenditures | | 1,735,706 | 1,458,203 | 1,612,673 | 2,134,987 | 2,176,795 | 3,490,629 | 2,869,025 |
| EXCESS (DEFICIENCY) REVENUES OVER | | 153,936 | 750,013 | 1,050,506 | 3,077 | 347,065 | (1,010,256) | (97,054) |
| FUND BALANCE - BEGINNING OF YEAR | | $ 898,435 | $ 1,052,371 | $ 1,802,383 | $ 2,852,890 | $ 2,855,966 | $ 3,203,031 | $ 2,192,775 |
| FUND BALANCE - END OF YEAR | | $ 1,052,371 | $ 1,802,383 | $ 2,852,890 | $ 2,855,966 | $ 3,203,031 | $ 2,192,775 | 2,095,721 |
| Reserve For Vehicle Replacement | | | | 47,998 | 65,183 | 83,039 | 115,776 | 175,000 |
| C. RECEIVABLE - NON PAYING CUSTOMERS | | | | | | | $ 84,658 | |
| D. REMAINING SCHOOL RECEIVABLES | | | | | | | $ 535,611 | |
| Unreserved Fund Balance | | $ 1,052,371 | $ 1,802,383 | $ 2,804,892 | $ 2,790,783 | $ 3,119,992 | $ 1,456,730 | $ 1,920,721 |

Section G-1 of this appendix contains backup calculations for certain results in Section 9 and additional cost analysis that did not prove useful, but is presented here to demonstrate their lack of utility (Section G-1). This is particularly true of regressions of normalized cost versus cost factors. Section G-2 of this appendix contains analysis of future cost to compare various cost scenarios using equivalent annual cost.

To compare costs from years greater than a year different from the year of this study (2003 dollars), the Consumer Price Index Urban (CPIU) was used (U.S. Bureau of Labor Statistics, 2005). CPIU was used because it is a common measure of inflation, it was similar to the Engineering News Review Construction Cost Index (CCI) from the Engineering News Record (ENR), yet CPIU reflects more broadly on how inflation than the CCI. As an example of similarity between the two indices, the CPIU adjustment factor from 1998 to 2003 agreed with the CCI to three significant figures. Because CPIU was similar to the ENR CCI and for consistency, CPIU was used to adjust both construction costs (e.g. treatment plant) and city stormwater costs that fund mostly non-construction activities such as inspection programs and maintenance of city infrastructure.

## G.1 COST SURVEY ANALYSIS

This section contains costs normalized by both number of households and population. Since cost per households is the most common in the literature, several regressions against this parameter are also presented in this section.

### *Survey Category Costs per Household*

Table G-1 presents survey category costs normalized by households.

**Table G-1. Survey Category Costs Per Household**

| Entity | Const. $/HH | IDDE $/HH | Ind/Com $/HH | Overall Man. $/HH | Pollution Prevention $/HH | Post. Con. $/HH | Pub. Ed. $/HH | Mon. $/HH | W. Man. $/HH |
|---|---|---|---|---|---|---|---|---|---|
| City of Corona | 1.36 | 0.53 | 2.29 | 8.09 | 18.34 | 0.34 | 0.72 | 0.18 | 0.00 |
| City of Encinitas | 7.12 | 2.07 | 2.75 | 5.38 | 22.16 | 0.64 | 1.76 | 3.20 | 0.52 |
| City of Fremont | 0.26 | 0.09 | 3.02 | 6.54 | 30.64 | 0.51 | 1.46 | 1.89 | 0.25 |
| Fresno-Clovis Area | 0.42 | 0.07 | 0.24 | 2.92 | 11.47 | 0.29 | 1.08 | 1.29 | 0.00 |
| City of Sacramento | 1.60 | 0.23 | 0.26 | 1.72 | 21.41 | 0.23 | 2.20 | 3.02 | 0.19 |
| City of Santa Clarita | 1.43 | 2.19 | 0.24 | 9.83 | 16.39 | 2.04 | 0.94 | 0.06 | 6.35 |
| | | | | | | | | | |
| Average | 2.03 | 0.86 | 1.47 | 5.74 | 20.07 | 0.68 | 1.36 | 1.61 | 1.22 |
| Median | 1.39 | 0.38 | 1.27 | 5.96 | 19.88 | 0.42 | 1.27 | 1.59 | 0.22 |
| Minimum | 0.26 | 0.07 | 0.24 | 1.72 | 11.47 | 0.23 | 0.72 | 0.06 | 0.00 |
| Maximum | 7.12 | 2.19 | 3.02 | 9.83 | 30.64 | 2.04 | 2.20 | 3.20 | 6.35 |

## *Survey Category Costs Per Capita*

Table G-2 presents survey category costs normalized by population.

**Table G-2. Survey Category Costs Per Capita**

| | Const. | IDDE | Indust. | Overall Man. | Pollution Prevent. | Post. Con. | Pub. Ed. | Mon. | W. Man. |
|---|---|---|---|---|---|---|---|---|---|
| | $/capita | | | | | | | | |
| City of Corona | 0.43 | 0.17 | 0.72 | 2.54 | 5.76 | 0.11 | 0.23 | 0.06 | 0.00 |
| City of Encinitas | 2.93 | 0.85 | 1.13 | 2.21 | 9.11 | 0.26 | 0.72 | 1.31 | 0.21 |
| City of Fremont | 0.09 | 0.03 | 1.03 | 2.23 | 10.46 | 0.17 | 0.50 | 0.65 | 0.09 |
| Fresno-Clovis Area | 0.15 | 0.02 | 0.09 | 1.02 | 3.99 | 0.10 | 0.38 | 0.45 | 0.00 |
| City of Sacramento | 0.64 | 0.09 | 0.10 | 0.69 | 8.04 | 0.09 | 0.89 | 1.22 | 0.08 |
| City of Santa Clarita | 0.50 | 0.76 | 0.08 | 3.41 | 5.69 | 0.71 | 0.33 | 0.02 | 2.20 |
| | | | | | | | | | |
| Average | 0.79 | 0.32 | 0.53 | 2.02 | 7.27 | 0.24 | 0.51 | 0.62 | 0.43 |
| Median | 0.46 | 0.13 | 0.41 | 2.22 | 7.19 | 0.14 | 0.44 | 0.55 | 0.08 |
| Minimum | 0.09 | 0.02 | 0.08 | 0.69 | 3.99 | 0.09 | 0.23 | 0.02 | 0.00 |
| Maximum | 2.93 | 0.85 | 1.13 | 3.41 | 10.46 | 0.71 | 0.89 | 1.31 | 2.20 |

## Construction Program Cost Normalizations

Table G-3 presents construction program costs normalized by several cost factors. In some cases, activity statistics were not available and, as such, normalization was not possible. In such instances, the average and median statistics are only based on the data available. Construction costs were normalized by number of active construction sites and inspections. The large variability in normalized cost may be a result of inconsistent reporting of these cost factors.

**Table G-3. Construction Program Unit Costs**

| Entity | Construction Cost | Active Sites | Construction $/active site | Inspections | Construction $/inspection |
|---|---|---|---|---|---|
| City of Corona | 53,382 | 41 | 1,302 | 564 | 95 |
| City of Encinitas | 169,751 | 40 | 4,244 | 401 | 423 |
| City of Fremont | 17,715 | 24 | 738 | 197 | 90 |
| Fresno-Clovis Area | 81,800 | N/A | N/A | N/A | N/A |
| City of Sacramento | 261,716 | 417 | 628 | 6,375 | 41 |
| City of Santa Clarita | 74,995 | 64 | 1,172 | N/A | N/A |
| | | | | | |
| Average | | | 1,617 | | 162 |
| Median | | | 1,172 | | 92 |

## Industrial and Commercial Program Cost Normalizations

Table G-4 presents industrial and commercial program costs normalized by several cost factors. In some cases, activity statistics were not available and as such, normalization was not possible. In such instances, the average and median statistics are only based on the data available. Industrial and commercial program costs were normalized by population, number of industrial and commercial sites, and number of inspections.

**Table G-4. Industrial and Commercial Program Units**

| Entity | Program Cost | Sites | Industrial $/site | Inspections | Industrial $/inspection |
|---|---|---|---|---|---|
| City of Corona | 89,916 | 3,050 | 29 | 600 | 150 |
| City of Encinitas | 65,596 | 417 | 157 | 266 | 247 |
| City of Fremont | 210,027 | 1,028 | 204 | 482 | 436 |
| Fresno-Clovis Metropolitan Area | 47,780 | N/A | N/A | N/A | N/A |
| City of Sacramento | 42,318 | N/A | N/A | 39 | N/A |
| City of Santa Clarita | 12,600 | 1,071 | 12 | 110 | 115 |
| | | | | | |
| Average | | | 101 | | 406 |
| Median | | | 93 | | 247 |

## Additional Regression Analysis

Many of the following regressions have outer and inner confidence limits. Though practically useless, they are displayed to indicate how much inaccuracy results from the regressions. The inner limits are the 90 percent confidence interval for the mean cost from the total population of



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"good" stormwater programs in California. The outer limits are the 90 percent confidence interval for cost of any one "good" California stormwater program.

Mean personal income appears to be the best indicator of total cost per household, but as a model not very useful because the predicted value nearly doubles when considering the confidence limits. Cost per household versus mean personal income is displayed in Figure G-1.

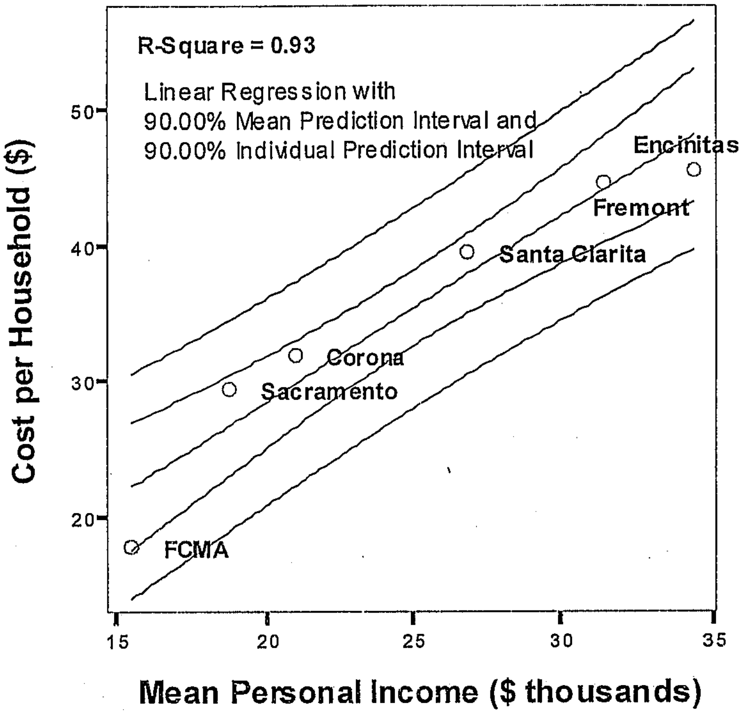


**Figure G-1. Cost Per Household versus Mean Personal Income**

In the regression of total cost per household verses income per household the theory is that the more money households bring in, the more a city would be able to collect for stormwater activities. However, this may not indicate more is accomplished because of higher cost for areas of higher income may limit how much can be accomplished. Cost per household versus mean household income is displayed in Figure G-2.

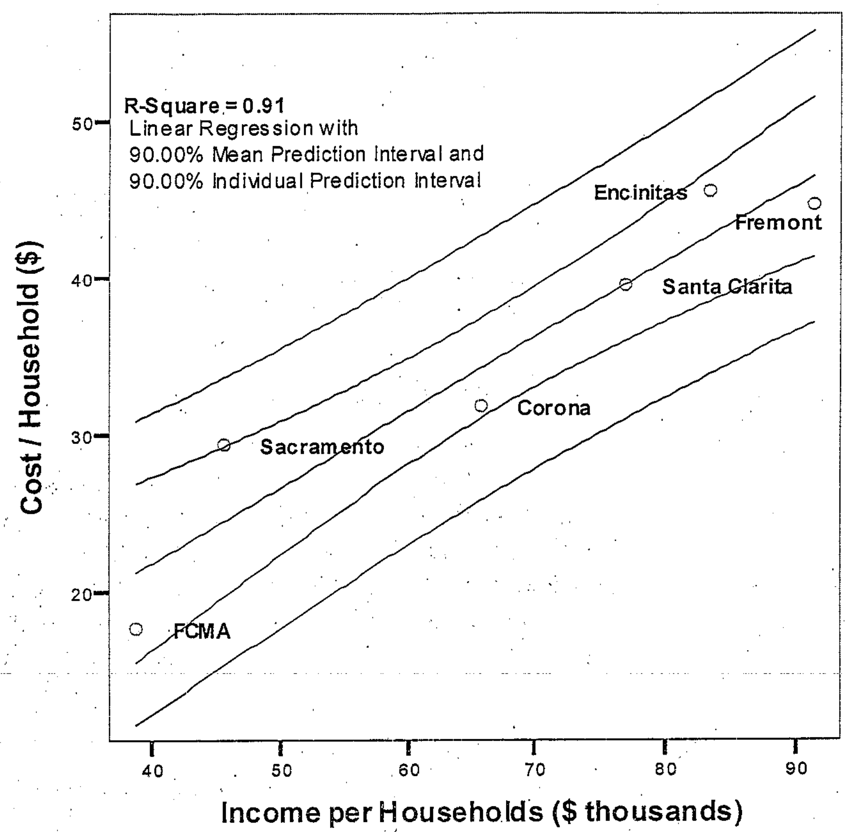


**Figure G-2. Cost Per Household verses Income Per Household**

As graphically demonstrated in Figure G-3, Fremont and Corona costs are particularly not well behaved in the regression of cost per household verses population. The conclusion is that city size is not a good predictor of stormwater cost per household (this is also discussed in Section 9.1). This is also demonstrated by the regression in Figure G-7.



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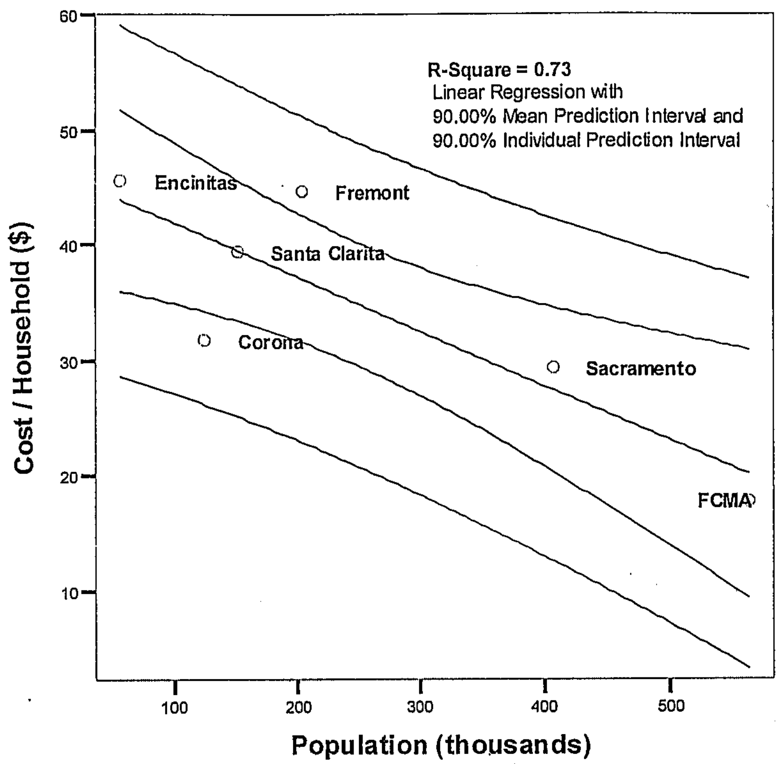


**Figure G-3. Cost Per Household verses Population**

Figures G-4 through G-7 show regressions using cost factors that are not useful in explaining costs. They are presented because there was some logic that they may be useful, and perhaps with more data they may prove to be helpful in more complicated models. However, they do not seem as important as the factors discussed qualitatively in Section 9.2 of the report. Each factor-years since incorporation, rainfall, income density, and incorporated area were considered for the following reasons:

- Years Since Incorporation was thought to increase cost because older cities would have higher maintenance costs
- Rainfall was thought to increase maintenance costs because of higher pollutant loads and a higher need for inspections
- Income Density was thought to generate a higher tax base for a given area. This would translate into more money available for stormwater.
- Area merely reflects the size of the city much like population. Area was considered because some activities, like street sweeping, may have been more dependent on area than population.

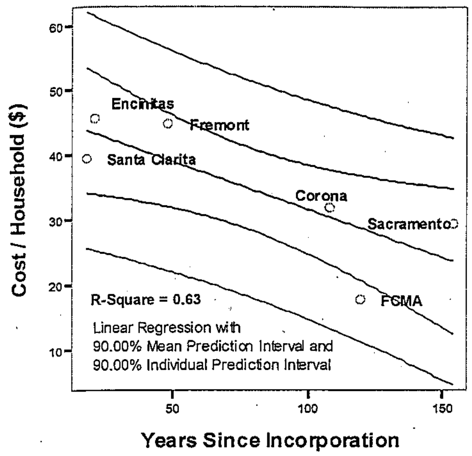


Figure G-4. Cost Per Household versus Years Since Incorporation

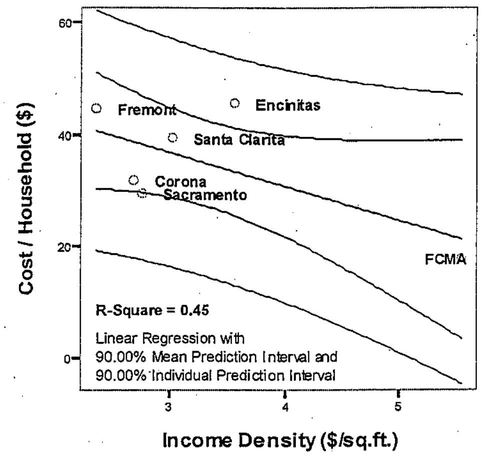


Figure G-5. Cost Per Household versus Annual Rainfall

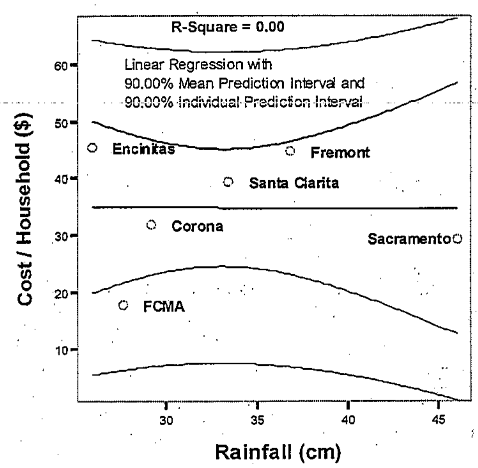


Figure G-6. Cost Per Household versus Income Density

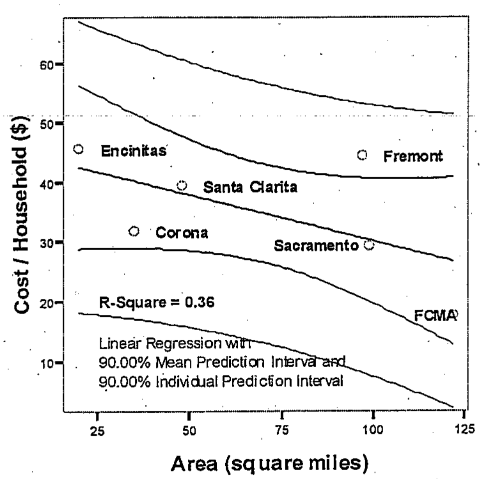


Figure G-7. Cost Per Household versus Area

Figure G-8 demonstrates that even though street sweeping is the highest cost activity, curb miles swept is not a very good predictor of stormwater costs. This is not surprising given the wide variability in street sweeping unit cost.

Another possible cost factor is type of land use but this could not be investigated due to land use data being inconsistent, or in several cases not available.

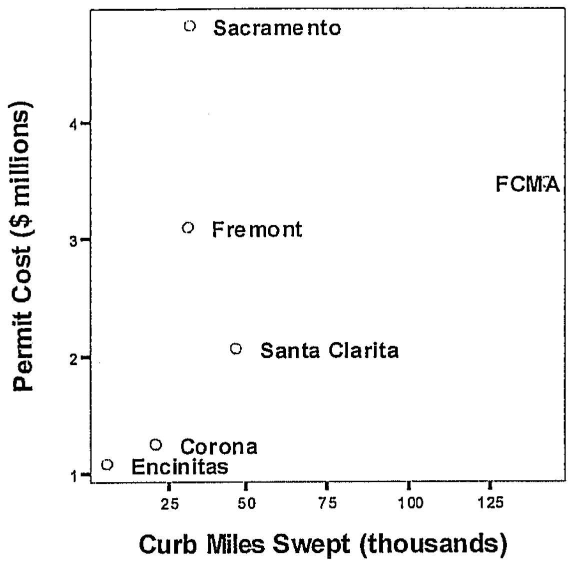


**Figure G-8. Permit Cost verses Curb Mile Swept**

# G.2. FUTURE COST ESTIMATES FOR THE LOS ANGELES AREA

Examples of future costs are restricted to the Los Angeles area where the future compliance cost has been a source of continued controversy. Costs estimates were taken from USC studies, the Los Angeles River Trash TMDL, the Ballona Creek and Estuary Metals TMDL, and the city of Los Angeles. TMDL estimates are for control of all sources of the pollutant, not just stormwater sources. These costs are presented since future permits will reflect TMDL requirements of the TMDL costs will be attributable to stormwater quality management.

To compare these cost estimates with each other, equivalent annual cost was calculated. Equivalent annual cost is calculated by taking the present worth of all capital and annual costs and then multiplying by 3 percent to get an infinite series of annual payments. Observations on these comparisons are discussed in the following sections. Use caution when comparing costs. Each type of cost addresses certain pollutant and source scenarios. TMDLs address sources other than stormwater and also address specific pollutants. Conversely, the USC studies focus solely on stormwater pollution control but address all pollutants causing impairment to water bodies.



A004996

## *Costs from the Description of Alternatives for Control of Stormwater Quality in the Los Angeles County (Devinny et.al., Task B: Appendix H)*

Task B is an assessment of regulatory policy to determine the intent to stormwater regulation regarding advanced treatment. Alternatives to advanced treatment that may comply with the intent of the regulations are described and costs are estimated. Task B was accomplished by faculty from the University of Southern California and the University of California Los Angeles and it is included as Appendix H.

The alternatives to advanced treatment focus on runoff reduction. The principle strategy is to reduce runoff by infiltration. The remaining runoff could be treated by conventional post-construction BMPs that are less expensive than advanced treatment. If certain discharges from these conventional BMPs still require advanced treatment, the cost of stormwater would be much less than if advanced treatment exclusively for stormwater pollution control. Based on this approach, costs for several alternatives are estimated for the area under jurisdiction by the LARWQCB. These alternatives do not include cost estimates for cases where advanced treatment is required because this need is assumed to be greatly limited. To compare these cost estimates with cost estimates from other studies, equivalent annual cost was calculated.

If source control[1] BMPs are sufficient to comply with regulations, the present worth cost is estimated at $2.8 billion ($84 million equivalent annual cost). The present worth cost, including low-tech treatment BMPs applied regionally, is between $5.7 billion and $7.4 billion ($171 million to $222 million equivalent annual cost) depending on whether cost per acre or cost per volume, respectively, were used in the estimates. Current level of effort in the Los Angeles area has only made limited progress in implementing the ideas described in Task B (Devinny, 2004). The current annual estimate of this effort is estimated at $18 per household (Radulescu and Swamikannu, 2003).

**Table G-5. Equivalent Annual Cost Per Household for Task B Alternatives**

| Cost Scenario for the Los Angeles Area | Equivalent Annual Cost, $/household |
|---|---|
| Current Effort | 18 |
| Alternative to Advanced Treatment: Pollution Prevention Scenario (Present worth 2.8 billion)[1] | 27 |
| Alternative to Advanced Treatment: Wetlands and Infiltration Basins Scenario, calculated using cost per area (Present worth 5.7 billion)[1] | 55 |
| Alternatives to Advanced Treatment: Wetlands and Infiltration Basins Scenario, calculated using cost per capture volume (present worth 7.4 billion)[1] | 71 |

1. Little progress has been made in implementing these scenarios (Devinny, pers. comm., 9/14/2004). These costs may be added to the current effort if existing programs continue to be required. Costs based on Devinny et. al. (Appendix H), see Table G-6 for equivalent annual cost calculation.

[1] The term "Non-structural BMP" was used by Devinny et. al. in Appendix H.



A004997

**Table G-6. Calculation of Equivalent Annual Cost Per Household for Task B Alternatives**

| | Present Worth, $10^9$ | Equivalent Annual Cost, $10^6$ | Los Angeles County Households | Normalized Equivalent Annual Cost, $/Household |
|---|---|---|---|---|
| Pollution Prevention[1] | 2.8 | 84.00 | 3,133,774 | 26.80 |
| Wetlands and Infiltration Basins, based on unit cost per watershed area | 5.7 | 171.00 | 3,133,774 | 54.57 |
| Wetlands and Infiltration Basins, based on unit cost per detention volume | 7.4 | 222.00 | 3,133,774 | 70.84 |

1. The pollution prevention scenario may include a small fraction of what cities are currently spending.

### *City of Los Angeles Bond Initiative and Future Bond Cost Estimates*

On July 8, 2004, the Los Angeles Times reported that the council members of the city of Los Angeles agreed to place a $500 million bond on the November ballot to clean up local surface waters in compliance with the federal Clean Water Act. The bond revenue would pay for the first five years of projects to help the city comply with certain Clean Water Act regulations. City officials estimate they will need an additional $435 million and $750 million to fully comply with requirements to reduce pollutants including bacteria. (Garrison, 2004) Using the total compliance costs ($500, $435, and $750 million) results in $40/household[2] in equivalent annual costs.

### *Los Angeles River Trash TMDL*

There are three cost estimates to comply with this TMDL (RWQCB, Los Angeles, 2001). Using catch basin inserts would have annual recurring costs of $66 million ($51/household), small separation units would have annual recurring costs of $183 million ($140/household), and large separation units would have annual recurring costs of $18 million ($14/household). It was not investigated why the cost of larger units is an order of magnitude less than smaller units.

Table G-7 presents the calculation worksheet for converting cost in the TMDL to equivalent annual cost per household.

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[2] A discount rate of 3% and 1,275,412 households were used to calculate equivalent annual costs per household.

**Table G-7. Cost Calculations for Los Angeles River Trash TMDL[1]**

| Scenario | 2001 dollars Capital Cost, $\$10^6$ | 2001 dollars Recurring O&M, $\$10^6$ | 2003 dollars Capital Cost, $\$10^6$ | 2003 dollars Recurring O&M, $\$10^6$ | Annualized Capital Cost[2], $\$10^6$ | Total Annual Cost, $\$10^6$ | Cost Per Household[3], $ |
|---|---|---|---|---|---|---|---|
| Catch Basin Inserts Only | 120 | 60 | 125 | 62.3 | 3.7 | 66.1 | 51 |
| Small Separation Units | 945 | 148 | 982 | 154 | 29.5 | 183 | 140 |
| Large Separation Units | 332 | 7.4 | 345 | 7.7 | 10.3 | 18.0 | 14 |

1. 2001 costs were adjusted for inflation to obtain 2003 cost figures (in millions, except cost per household).
2. A rate of 3 percent was used to calculate these costs.
3. Based on 1,300,000 households in the Los Angeles River watershed.

## *Ballona Creek and Estuary Metals TMDL*

The Ballona Creek watershed covers 128 square miles in Los Angeles County. Open space comprises 17.5 square miles and water comprises 0.75 square miles of the Ballona Creek watershed. Cost estimates are based on the remaining 110 square miles.

Infiltration trenches and sand filters were assumed to cover 40 percent of the urbanized portion. The remaining costs were an estimate of approaches including source control and pollution prevention measures (RWQCB, Los Angeles, 2004). The equivalent annual cost per household in the watershed are estimated to be between $70 and $75.

It is noted in the TMDL that the retrofit cost per area for these devices in the Caltrans BMP Retrofit Pilot Study was nearly 10 times greater for stand alone retrofit projects. It is expected that cost will be reduced if BMPs are installed within larger reconstruction projects (Caltrans, 2004).

Table G-8 provides cost information relating to compliance with this TMDL. Annualized construction costs were calculated by multiplying the construction cost by three percent. Ranges of total annual cost were determined based on the estimates. The low side of the range includes the FHWA annualized construction cost and the USEPA recurring maintenance cost. The high side of the range includes the USEPA annualized construction cost and the recurring maintenance cost. It was assumed that 40 percent of the urbanized portion of the watershed would need to be treated by structural BMPs. Of this 40 percent, infiltration trenches would treat 20 percent of the watershed and sand filters would treat the other 20 percent. The remaining 60 percent would include enhanced pollution prevention activities (e.g. street sweeping).

**Table G-8. Cost Calculations for Ballona Creek and Estuary Metals TMDL**

| Cost Basis | Construction Cost | Recurring Maintenance Cost | Annualized Construction Cost[2] | Total Annual Cost[3] | Cost Per Household |
|---|---|---|---|---|---|
| USEPA estimate (1999) | 336 | 36 | 10.1 | 46.1 | 75 |
| FHWA estimate (1994) | 245 | not reported | 7.4 | 43.4 | 70 |

1. Dollars in millions (except cost per household).
2. A rate of 3 percent was used to calculate these costs.
3. Total cost for the FHWA includes their annualized construction cost and the USEPA recurring maintenance cost.

## *California Willingness to Pay for Statewide Clean Water*

According to a survey (Larsen and Lew, 2003), California residents are willing to pay on average $180 per year to remove all impairments from all water bodies in the state (not just urban areas). Potential limitations with this estimate are discussed here.

This assumes cleaning water from all sources of contaminants, not just urban stormwater sources so this may not be directly compared to the cost of stormwater programs. Also, the cost of stormwater programs is only what the cities pay per household. It does not include other cost passed along to the household or individual. These costs are not incurred by the cities but by developers complying with the construction permit and Standard Urban Stormwater Mitigation Plan (SUSMPs) and industries complying with the industrial permit and businesses and individuals complying with the stormwater permit.

The survey also had 40% non-responders. This may overestimate the willingness to pay based on the assumption the people that do not respond to an environmental survey are less likely to care about environmental issues and people that do not care are less willing to pay for water quality improvement. It does not appear that these issues were addressed by the study.

The study did adjust the willingness to pay based on the average education of Californians. The sample population surveyed had a longer education than average Californians and a statistically significant correlation was found between willingness to pay and years of education. However, it is unclear from the report if the correlation was extrapolated to years of education below that of the surveyed population. This would assume that the relationship between education and willingness is the same for lower years of education.

## *Comparing Task B Alternatives to Advanced Treatment and TMDL Cost Estimates*

The 'alternatives' described in Task B are meant to address all pollutants, while the metals or trash TMDLs only address single type pollutants yet the cost estimate is higher. In both cases, advanced treatment is not considered and common BMP costs are used. This comparison indicates the variability in cost estimates for similar stormwater scenarios. Comparing the two TMDL maximum cost estimates also demonstrate the sensitivity of cost estimates to BMP deployment scenarios. Metals are more difficult to remove than litter and thus it is expected the cost would be less, however, the metals TMDL assumed only 40% of the watershed would be retrofitted with treatment BMPs while the trash TMDL assumed 100% deployment of litter removal BMPs. A major cause of variation in these estimates is that the unit cost used in these estimates vary from study to study. For example, the TMDL estimates use BMP unit cost that are around 10 percent of the unit cost reported by Caltrans, but the Caltrans experience was in a fully developed watershed (Los Angeles and San Diego urban areas) where utility conflicts and space limitations are common. An additional factor is that the Caltrans experience was in a stand-alone retrofit environment which likely caused cost increases over projects integrated into larger projects (Caltrans, 2004). This indicates that costs are extremely site specific and estimating regional cost is very difficult.

Table G-9 compares current costs from the California survey with various estimates to meet certain stormwater management goals. Table G-9 also includes a comparison to the California willingness-to-pay.

**Table G-9. Equivalent Annual Cost per Household Comparisons between California Cost Survey Results and various estimates for water quality Los Angeles Area Future Cost Estimates[1]**

| Range of Current Cost from Six Surveyed California Cities | | Range of Alternatives to Advanced Treatment[2] | | Maximum TMDL Estimates | | City of Los Angeles Bond Estimates | Statewide Clean Water Willingness To Pay Estimate[3] |
|---|---|---|---|---|---|---|---|
| | | | | Ballona Creek Metals | L.A. River Trash | | |
| 18 | 46 | 27 | 71 | 75 | 141 | 40 | 180 |

1. Calculations are presented in Tables G-10 through G-12 and are based on the following sources for each column respectively: survey results, Devinny et al (2004), Gordon et al (2002), LARQCB (2004), LARQCB (2001), Garrison (2004), and Larsen (2003).

2. Calculated from Task B in Appendix H. Low range is the cost for attaining full compliance using only source control. High range is the cost for attaining full compliance using only treatment BMPs (low tech) estimated on capture volume.

3. Responses were not received from 40% of the mailed surveys. The survey question was for restoring water quality for all waters throughout the state from all impairment, not just within a city or region and not just for impairment from stormwater pollution (Larsen and Lew, 2003).

## *Cost of Advanced Treatment (Gordon et.al.)*

This study presents a comprehensive analysis of the potential costs required to meet new and emerging stormwater regulations in the Los Angeles area. It assumes that advanced treatment of storm flows will be required to meet current and anticipated federal and state water quality standards. The study presents three scenarios in treatment plant size and distribution among 65 sub-basins. These scenarios are 480 plants per sub-basin, one plant per sub-basin, or one plant per city. Three runoff quantity scenarios (0.5 inch, 1.25 inch, and 2.25 inch storms) were assumed for each treatment plant scenario. The least expensive alternative for the 0.5 inch storm was using 480 plants per sub-basin. This storm depth was chosen because it was closest to the 0.75 inch storm required for treatment in the Los Angeles SUSMP. Table G-10 calculates the equivalent annual cost per household for two treatment plant scenarios for treating the 0.5 inch storm.

**Table G-10. Equivalent Annual Cost Calculation for Costs from Gordon et al.**

| 70% Capture of Annual Rainfall (0.5 inch capture volume) | Capital Cost, $\$10^9$ | O&M Cost, $\$10^6$ | Equivalent Annual Cost (EAC)[1], $\$10^6$ | EAC/Household, $ |
|---|---|---|---|---|
| 130 small plants | 48 | 91 | 1,540 | 491 |
| 65 large plants | 44 | 127 | 1,439 | 459 |

1. Cost includes collection system and land cost and maintenance of the collection system (Gordon et al. p. 40-41, 2002).

### *Comparing Alternatives to Advanced Treatment to Advanced Treatment Estimates*

Since some advanced treatment may be required, the future cost will lie between the alternative scenarios estimate and the advanced treatment estimate. Based on the assumption used by the Devinny study, future costs for the Los Angeles area appear to hinge on the ability to reduce stormwater runoff volumes and on the ability to control pollutants through source control.

### *Significance of Future Compliance Cost Estimates*

The range of cost estimates presented for the Los Angeles area should not be used for other areas of California. TMDL compliance, and thus ultimate permit compliance, is only addressed for certain pollutant types in the Los Angeles area. TMDL implementation plans will vary in complexity, pollutant being addressed, other non-stormwater sources, and watershed size. Some watersheds may not have a TMDL. Determining future cost for other California communities is a case-by-case exercise.

## G.3 REFERENCES

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# Alternative Approaches to Stormwater Quality Control

*Prepared for the Los Angeles Regional Water Quality Control Board*

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## EXECUTIVE SUMMARY

### Background

A recent, widely debated study entitled *An Economic Impact Evaluation of Proposed Storm Water Treatment for Los Angeles County* projects extremely high costs for compliance with stormwater quality regulations (Gordon et al., 2002). These estimates followed from the study's fundamental assumption that the only way to comply with water quality regulations is to capture most or all of the flow and subject it to advanced treatment, and to do so at rates equal to peak runoff rates. *In contrast, this report shows that there are far less expensive approaches available that, should they be implemented, will achieve high levels of compliance with current federal water quality standards.*

### Alternatives Considered

This report reviews present federal and state regulations and regulatory policy to determine whether advanced ultrafiltration treatment of the entire runoff flow is required to meet water quality standards, or whether compliance can be achieved through the widespread adoption of the various "best management practices" (BMPs) more commonly used for runoff quality control. The work identified and analyzed alternative measures that can be employed to meet present federal and state water quality standards. Particular attention was paid to strategies that concern ground water recharge, pollutant source control, and runoff detention, capture, and BMP treatment.

The report reviews possible approaches for controlling runoff water quality in the Los Angeles Region (the jurisdiction of the Los Angles Regional Water Quality Control Board) and presents a conceptual regional plan, including rough cost estimates. The study pursued a broad approach, providing an evaluation of total costs and benefits for the region, including those for municipalities, businesses, and individuals. The objective of the study was to outline a complete solution to stormwater quality problems, i.e., the plan is intended to meet the requirements of the stormwater permit and Total Maximum Daily Loads and provide acceptable water quality for the area. The alternatives of best management practices (BMPs) for control of individual pollutants (source control), and if necessary, a regional system of wetlands and infiltration facilities to provide final treatment and groundwater replenishment were chosen. These will be much cheaper than advanced treatment plants, and will provide benefits whose value exceeds costs.

### Assumptions Made for Determining Costs

Following the review of possible remedial actions for stormwater pollution, a conceptual plan for the Los Angeles Region was developed. It was predicated on the following assumptions:

Because source control is always cheaper than cleaning polluted water, efforts should begin with preventing the release of pollutants to runoff. This includes measures like litter control, improved street cleaning, improved industrial housekeeping and others. Such approaches may constitute sufficient control for runoff coming from residential areas, so that these areas will require no further action.

For new residential development, anecdotal information indicates that landscaping that captures and infiltrates the first-flush storm will be of comparable cost to traditional landscaping, and should therefore be used. For commercial construction, costs may be higher, and adequate regional facilities might be substituted.

Where non-structural BMPs will not be adequate, or where implementation is very expensive, efforts must expand to include regional wetlands and stormwater parks (multiple-use infiltration basins).

Large portions of the Los Angeles Region are already built out to various degrees, constraining available stormwater management solutions. This report assumes that 1000 square miles can be characterized as "low density", and that these regions can be served by a combination of source control, treatment wetlands, and infiltration systems. Another 1000 square miles is "high density" and can be served by source control and infiltration systems. About 50 square miles are "extremely high density" (such as downtown areas) and will require more sophisticated infiltration or treatment devices that occupy smaller areas.

**Estimated Costs**

Total costs for compliance with runoff water quality regulations were predicted to be between $2.8 billion (if non-structural systems are sufficient for the entire region) to between $5.7 billion and $7.4 billion (if regional treatment or infiltration systems must also be constructed throughout the entire area). It is likely that regional systems will be required for at least some, but not all, of the area, so that the final costs will be somewhere between these extremes.

- Enforcement of littering, pet waste, and chemical use ordinances is expected to cost about $9 million per year.

- Public education will cost about $5 million per year. A program to detect and prevent illicit discharges to the system will cost about $80 million per year at first, but can be reduced to much lower levels as compliance is achieved.

- Increased cleaning of storm drains will be needed if regional solutions are not used, and will cost about $27 million per year.

- Trash discharges to receiving waters can be controlled by installing screening devices on catch basins, enforcing litter laws, and improving street cleaning services. Estimates are that the immediate cost of instituting these measures will be about $600 million over the Los Angeles Region.

- During periods of low flow, runoff water should be diverted to existing wastewater treatment plants. Construction costs for this effort will be about $28 million.

- Trash control and removal of particulates and their associated pollutants can be facilitated by improved street cleaning. It is expected that this will cost $7.5 million per year more than current street cleaning programs, with a present worth of $250 million.

- On-site BMPs required for individual firms might cost about $240 million. Costs associated with compliance with the ¾-inch rule for new construction will be a modest fraction of construction costs.

- With regard to structural BMPs, total costs (regional wetlands and infiltration systems) were first estimated by determining the costs per square mile of drainage area incurred at other sites, and multiplying by the area over which they will be applied. Wetlands for the "low density" areas were estimated to cost $420,000 per square mile of drainage area, for a total cost of $420 million. Infiltration systems for the "high density" areas were estimated to cost $3.7 million per square mile of drainage, for a total cost of $3.7 billion. More sophisticated treatment BMPs (such as sediment traps and oil adsorbers) for the "extremely dense" areas were estimated to cost $33 million per square mile of drainage, for a total of $1.7 billion. Thus total new facilities costs are $5.8 billion.

- A second method for estimating structural BMP costs utilized costs per acre-foot of retention capacity as determined by the Los Angeles County Department of Public Works Sun Valley Project. Presuming that runoff from a ¾-inch storm must be captured in the low-density, high density, and extremely high density areas with runoff coefficients of 0.4, 0.6, and 1.0, costs are $53,000, $98,000, and $470,000 per acre-foot, respectively. The overall facilities cost estimate using this method is $4.0 billion.

**Estimated Benefits**

There are substantial benefits to the examined approaches that extend beyond the value of stormwater quality control. Reductions in pollutant releases will improve public health and neighborhood livability. Restoration of the hydrologic cycle will replenish groundwater reservoirs, reduce flood risks, and provide greenspace for recreation and wildlife habitat. It was determined that the total value of benefits from the alternatives for runoff quality control described will exceed the costs. Total benefits for the non-structural stormwater quality control programs in the Los Angeles Region are estimated at $5.6 billion. Implementation of the non-structural and regional measures throughout the Los Angeles Region would have benefits worth $18 billion.

- Reduced need for flood control is expected to save about $400 million.

- Property value increases from additional greenspace and bodies of water are expected to amount to $5 billion over the Los Angeles region.

- Additional groundwater supplies created by infiltration will have a current worth of about $7.2 billion.

- "Willingness to pay" surveys in similar circumstances suggest that the public amenity value of avoiding stormwater pollution of local bodies of water is about $2.5 billion.

- Cleaner streets are worth about $950 million.

- Improved beach tourism will bring in about $100 million.

- Preservation of the nature's services in the marine coastal zone, such as nutrient recycling and chemical maintenance of the atmosphere, is worth about $2 billion.

- Reduction of sedimentation in local harbors will save $330 million.

- Improvements in public health associated with reduced exposure to fine particles from streets are likely significant, but could not be quantified.

**Recommendations for Immediate Action**

Municipalities that have the responsibility for meeting runoff quality regulations should take some immediate steps.

- Outreach programs, explaining to citizens the need for runoff quality control and discouraging illegal discharges such as littering, should begin.

- Data should be collected on the stormwater discharges from subwatersheds to determine what BMPs are workable, and general plans should be updated to include policies that promote stormwater control.

- An administrative structure should be established which includes the relevant stakeholders and funding agencies for each watershed (such as watershed councils).

- Funding plans should be developed.

- Building codes that work against runoff quality control should be changed immediately—in particular, all parking lots built from now on should also be stormwater infiltration systems.

- All new street cleaning equipment should be high-quality vacuuming systems. Appropriate agencies should be encouraged to use the latest microbiological techniques to investigate sources of pathogenic organisms in runoff, so that mitigation efforts can be optimally designed.

# INTRODUCTION

This report identifies and analyzes alternatives for control of stormwater runoff in Los Angeles County. A recent, widely debated study entitled, *An Economic Impact Evaluation of Proposed Storm Water Treatment for Los Angeles County* projects extremely high costs for compliance with stormwater quality regulations (Gordon et al., 2002). These estimates followed from the study's fundamental assumption that the only way to comply with water quality regulations is to capture most or all of the flow and subject it to advanced treatment, and to do so at rates equal to peak runoff rates. As this report shows, however, there are far less expensive approaches that, if implemented, can achieve high levels of compliance with current federal water quality standards.

A broad approach was taken: an evaluation was made of total costs and benefits for the region, including those for municipalities, businesses, and individuals. A complete solution to stormwater quality problems was considered—that is, the plan is intended to meet the requirements of the stormwater permit and Total Maximum Daily Load and provide acceptable water quality for the area. The recommendations for steps to be taken are not limited to the Los Angeles Regional Water Quality Control Board (LA Regional Water Board). Action by other governmental agencies will also be required. The study begins with a brief description of runoff sources and contaminants. A review of present federal and state regulations and regulatory policy to was done to determine whether advanced ultrafiltration treatment of the entire runoff flow will be required, or whether compliance can be achieved through the widespread adoption of the various "best management practices" (BMPs) more commonly used for runoff quality control. The study then identifies and analyzes alternative measures that can be employed to meet present federal and state water quality standards. Particular attention is paid to strategies that facilitate ground water recharge, source control measures, storm water detention and capture, and BMP treatment. While prevailing uncertainties make an overall cost estimate only approximate at this time, costs of specific approaches are illustrated with examples. Financial benefits, such as those regarding groundwater replenishment, more appealing beach environments, improved public health, and the creation of additional urban green space, are also addressed in the report. Clearly, water is a scarce resource in this region of the country, and economic evaluations of different management techniques for stormwater runoff must also consider the benefits of improved water quality and water supply as well as flood control. Prior to reviewing federal and state water quality regulation and policy, this study provides an overview of more general policy and regulation theory.

## Runoff

The bulk of urban runoff is generated during rainfall events, and can properly be termed stormwater. This flow is extremely irregular, especially in Southern California, where most days are dry, and measurable rain occurs on average of only 32 days per year. Total rainfall in the area is modest, averaging about 16 inches per year. A large storm in this area might drop as much as three inches of rainfall in 24 hours, but this is still much less intense than typical rainfall events in other states, such as those on the East Coast.

Even so, high flows and flooding do occur in Southern California because of the topography. Water from large watersheds drains into local rivers, and slopes are steep, so that rainfall is rapidly collected and concentrated.

Water also enters the storm drains from non-rainfall sources. Sprinklers left on overnight, car washing, and hoses used to clean sidewalks and driveways generate smaller streams sometimes called nuisance flows. These flow in the storm drain system all year, and with residual stream flows (and in a some areas, recycled wastewater), constitute dry-weather flow. The terms "stormwater" and "runoff" are often used interchangeably. However, it is important in some cases to recognize the difference—stormwater arrives suddenly in huge amounts, while nuisance flows are much smaller and run all year.

Urbanization of the landscape substantially changes the amount and composition of runoff. Because less water infiltrates (percolates) into soils, the total amount of runoff is increased. Because the water runs off pavement more rapidly, it is concentrated to make peak flows higher. Recharge of groundwater is reduced, and the shallow groundwater that feeds some streams dries up, so surface flows decrease in some areas. Surface flows may increase during dry weather in other areas because of nuisance flows from over-irrigation and car washing. In general, the storage and buffering effects of soils and groundwater reservoirs are reduced. Runoff flowing through vegetation, or entering and leaving shallow groundwater, is subject to the effects of filtration and biodegradation, which has a considerable purifying effect. Water runoff from pavement is not cleaned, and indeed is contaminated by whatever dirt and pollutants are on the pavement.

**Pollutants**

The cities of Southern California use "separate" systems, meaning stormwater is collected apart from the wastewater generated by toilets and showers. The wastewater enters a closed network of pipes and is carried to treatment plants. Stormwater may initially flow in underground conduits, but eventually passes to open flood control channels, rivers, and the ocean. This storm water drainage system is called a Municipal Separate Storm Sewer System (MS4). Runoff pollutants are different in nature from those in sewage. Pathogens are present, but in far smaller concentrations, as are nutrients such as phosphorus and nitrogen. There may be more petroleum hydrocarbons, dust, sediments, and settled air pollutants in runoff, but total organic content in runoff is usually much lower than in wastewater.

The pollutant load of stormwater varies greatly with location. The water contains pollutants that wash off rooftops, parking lots, industrial facilities, and the streets. Pollutants may also be discharged illegally, when individuals pour motor oil into the storm drains or industries release toxic pollutants.

Water flowing in the streets picks up trash, dust, dirt and other materials that have been deposited on the pavement. The dust includes fine particles of rubber from tire wear, settled air pollutants, trace metals from brake pads and other mechanical sources, and pet feces. Cars drip motor oil onto the pavement and the early flows of fall may carry a petroleum sheen.

Stormwater quality protection measures may be placed in three general categories. Infiltration allows percolation of the water into the ground, relying on the soil to remove pollutants from the replenishing groundwater and eliminating the discharge to runoff. Source control measures prevent the release of pollutants, so that the water is never contaminated. Treatment systems remove the pollutants from the stormwater before it reaches the ocean.

**Runoff Sources and Quality**

Stormwater and runoff come from a great variety of sources and carry a varied suite of pollutants. There are many approaches to the task of protecting receiving waters, and the best choice depends on stormwater source and quality. Runoff from a residential area of single-family homes, for example, is unlikely to carry industrial pollutants, but may have small amounts of oil and grease from roads, microbiological contamination from pet feces., and dissolved nutrients from fertilizers. These are readily removed by filtration in soil, so groundwater recharge, with its additional benefit of replenishing aquifers, is a good choice. Runoff from construction sites is less likely to carry harmful microorganisms, but may have heavy loads of sediment. The best choice here is to use dikes, detention ponds, and other measures to allow the sediment to settle out of the water before it is percolated to groundwater or released to storm drains. The dispersed and difficult-to-control pollutants of urban commercial areas may best be dealt with by providing regional solutions, such as parkland designed to serve simultaneously as a flood control basin, a groundwater recharge site, and a sedimentation basin for large amounts of water.

*Streets*

Streets, particularly those in dense commercial areas, are the most difficult source of urban runoff to manage. They receive litter, dust and dirt, air pollutant particulates, pet feces, occasional human waste, trace metals and oil from cars, various illegal discharges, and other pollutants. Because they are the first part of the stormwater collection and transport system, they receive and pass on pollutants that are carried away from parking lots, commercial establishments, and industries.

*Exposed Commercial Activity*

Manufacturing and other commercial activities, even those dealing with hazardous materials, have no effect on stormwater quality if the work is carried out under cover. However, for some large-scale activities, such as oil refining, this is not practical. Rain falling on machinery, materials, or contaminated surfaces can pick up pollutants. Measures can be taken to cover individual activities, or treatment systems can be installed to clean the water before release.

*Construction Sites*

Frequently, the first step taken in construction of new facilities is to clear the land of vegetation and pavement. The exposed soil is highly vulnerable to erosion by rainfall, and the movement of trucks and machinery can "track" soil to the adjacent streets.

*Residences*

Single-family homes are a source of some pollutants. Roof runoff will contain dust, bird feces and settled air pollutants. Runoff from gardens may contain pesticides and fertilizers. Occasionally, homeowners will (illegally) dispose motor oil or paint waste into storm drains. For the most part, however, runoff from neighborhoods of single-family homes is relatively less polluted (if household toxics such as pesticides are properly used). Multiple-family residences produce many of the same pollutants, but typically have a higher ratio of rooftop and impervious surface to permeable landscaping, so that more water runs off.

*Commercial Rooftops*

Roof runoff from commercial facilities may be slightly polluted with air pollutant dusts, bird droppings, hydrocarbons from roof tar, and occasionally, some trace metals from rooftop machinery. The contaminants present may be very similar to those found on residential roofs, but handling the runoff may be more difficult because commercial areas have a high ratio of roof area to land area, and often have little landscaping.

*Parking Lots and Landscaping*

A significant fraction of urban land is devoted to parking lots. Parking lots are commonly polluted by litter, heavy metals from auto-parts and road wear, and by oil leaking from cars. Spilled food is present near establishments that sell food, and pet feces, bird droppings, and settled air pollutants will also be present, and all of these can be washed away in the runoff. Virtually all parking lots are designed for rapid drainage to the street or storm drain. Indeed, where grass or other plantings are present, these are commonly surrounded by curbs that prevent flow of the water from the lot into the soil. Many designs, in fact, promote runoff from the vegetation to the pavement.

## ASSESSMENT OF REGULATORY POLICY

### Overview of Policy and Regulation Theory

This report, in identifying and assessing BMPs, takes a strategic regulatory planning approach to managing stormwater runoff in Los Angeles County. Strategic regulatory planning involves a close examination of the legislative goals concerning the given policy. The ultimate end of strategic regulatory planning is to control behavior through methods that agree with legislative goals and societal values regarding the issues at hand. Thus, a strategic approach demands careful consideration first of whether enforcement is appropriate; and second, if enforcement is appropriate, to what degree should the parties involved be pressured to comply; and third, how coercive should the regulatory devices be? Compliance with existing laws and regulations, in this case the provisions of the federal Clean Water Act and state law, is a major goal of the strategic regulatory planning process.

How compliance is defined can vary markedly depending upon the actors involved and the policymaking context. In this sense "compliance" means the degree to which members of a target group conform to the directives of an agency, court, legislative body, or some other governmental agency. One way to determine whether members of a target group are in compliance with an environmental law is to monitor levels of pollution on a regular basis. We assume that the greater the number of individuals and firms that are in compliance with rules, the more likely pollution will decrease in a given locality.

When legislators pass laws, they generally expect them to be vigorously enforced and fully obeyed. Only idealists, however, actually believe that this is possible or even necessary in all cases. Political and economic factors usually force policymakers to take a more realistic approach to enforcement by setting a desired and attainable level of compliance prior to program implementation. At this stage, policymakers must consider whether 100 percent compliance is necessary. If not, they must determine what degree of compliance is needed in order to meet environmental quality goals. While the desired degree of compliance is often only a rough estimate, several factors must be kept in mind. Policymakers must take into account, for example, the extent to which members of a target group are making a "reasonable" effort to change their behavior and follow the law.

If it is either unrealistic or undesirable to aim for total compliance on the part of the target population, a clear decision rule must be formulated concerning enforcement priorities. In a policy area where polluters vary a great deal in size and how much they pollute, for example, it is commonly most prudent to concentrate enforcement efforts on the largest polluters. If firms are roughly the same size and pollute about the same amount, however, alternative guidelines for identification and discrimination must be set. For example, will businesses be selected randomly for monitoring and inspection? Is systematic enforcement, perhaps based on location, possible? Or, is self-regulation the preferable approach? The decision rule should relate to the strategic goals, resources, and motivations of all those involved. Further considerations include the legal authority for enforcement, the resources of the enforcement agency, and the fragmentation of the enforcement agency (or agencies).

In the ex post review/revision stage, policymakers determine the effectiveness of the regulatory program after it has been implemented. Feedback and evaluation are used to assess program performance. Legislative goals are used as a guide in determining whether regulatory approaches are succeeding or failing.

If policymakers determine that the program goals are still desirable, they will continue the same course of action. If they determine that the goals are being met, they will either maintain present enforcement levels or perhaps decrease enforcement efforts. The latter decision should only be made if policymakers believe they can save time and money and feel reasonably certain that compliance rates will not suffer. Appropriate and immediate action is required, of course, if the objectives are no longer desirable or if the objectives are not being achieved. In nearly every case, the aim of policy revision will be improvement in compliance and environmental quality. According to Ingram, the implementation phase of a statutory program "should contribute toward policy improvement or the evolution toward more tractable problems for which there are more doable and agreeable responses." (1990:476) Realization of the statutory goal, therefore, is not the only way to gauge the success of program implementation.

The conceptual perspective for the selection of BMPs analyzed in this report relies on Lowi's (1964) policy classification scheme, with further elaboration by Salisbury (1968). Lowi classifies policies as distributive (non zero-sum policies in which nearly everyone benefits), redistributive (policies that approach zero-sum, in which some benefit and some lose), and regulatory (policies that also tend toward zero-sum, and in which government prescribes rules of behavior for particular groups). Salisbury added a critical dimension to Lowi's typology by identifying self-regulation policies as a fourth policy type. Self-regulation policies are frequently offered as a noncoercive alternative by sectors of society targeted for external regulation, and they are invariably non zero-sum. These policies also impose constraints upon a group, but are perceived only to increase, not decrease, the beneficial options to a particular segment of the population.

Under this classification scheme, policies are *either* self-regulatory *or* regulatory. Thus, the Lowi and Salisbury typologies suggest that regulatory policies are either noncoercive (through self-regulation) or coercive (through direct command-and-control regulation). In the real world, however, regulatory devices tend to fall at different points along a continuum of coerciveness. In other words, devices intended to control behavior tend to vary according to their restrictiveness. Non-coercive approaches (through self-regulation) occupy one end of the continuum while coercive approaches (through direct command-and-control regulation) occupy the other end.

Conceptualizing regulation in these terms provides water quality policymakers a flexible framework in which to assess alternative regulatory mechanisms. Water quality policymakers have a menu of regulatory approaches from which to choose, and careful thought must be given as to which regulatory devices are best suited to control stormwater runoff without being unnecessarily harsh. If members of the target population (e.g., citizens, small businesses, municipalities, etc.) unanimously believe that stormwater regulations and deadlines are too restrictive and unfair, they will likely ignore what they are being told to do. At the same time, if regulatory devices are too weak and not sufficiently coercive to lead to improvement in water quality, then efforts to control stormwater runoff will fail. Water quality policymakers, therefore, must be familiar with the target population and possess considerable information before they select the most appropriate regulatory mechanisms that embody the level of coercion necessary to achieve an optimum degree of compliance.

Cost is a second dimension that characterizes regulatory mechanisms. Cost here refers to the amount of money government must spend to administer a particular regulatory approach (cost to the regulated community will be considered later). In general, the most coercive activities (e.g., imprisoning polluters) require the greatest government involvement and therefore are more expensive to administer than the least coercive activities (e.g., economic incentives). Limited government revenues obviously make this an important variable. This is especially the case in current government efforts to control stormwater pollution.

The total cost and coerciveness of the selected regulatory program represent the overall government effort necessary to attain compliance and control water pollution. Compliance can be achieved in varying degrees and is best conceptualized along a continuum ranging from avoidance to adherence. Under optimal conditions (e.g., a harmonious political environment), policymakers will be able to use the least coercive enforcement techniques (e.g., reporting by firms and municipalities and formal compliance tracking) at the least cost to achieve full compliance. The expectation is that least coercive mechanisms are always preferable to more coercive mechanisms if only because the former devices are more cost-effective. In contrast, extremely restrictive enforcement arrangements (e.g., court injunctions) will necessitate direct government involvement and thus require substantial cost. Under ideal conditions, therefore, policymakers will select regulatory devices that are the least coercive and least costly and that lead to compliant behavior.

Unfortunately for policymakers, optimal conditions are rare. Many times the conditions that do exist (e.g., a lack of agency funds or a small staff) tend to diminish the effectiveness of the least coercive approaches, often to the point where the outcomes are in danger of moving toward avoidance behavior. In order to prevent outcomes from moving in this direction, policymakers must select techniques, either singularly or in combination, that are affordable and sufficiently coercive to produce compliant behavior.

Naturally, policymaking is a dynamic process and circumstances tend to change over time. Decision makers are continuously gauging the potential impact of given conditions on regulatory mechanisms and making adjustments as they see fit. Eventually, they may be forced to adopt expensive and restrictive approaches that will result in compliant behavior in an attempt to prevent outcomes from moving toward avoidance behavior. When accurate information is available and incorporated into deliberations, policymakers usually will achieve the greatest level of compliance possible with the least effort and expense regardless of the conditions that exist at the time. This underscores the importance of obtaining the most accurate data available as changes occur over time.

In a pluralist, multi-level system like the United States, some communities may favor avoidance behavior in the face of unpopular regulations. While such situations may arise from time to time, in most cases policymakers will want their regulatory devices to achieve the highest level of compliance possible under given conditions.

*Stormwater Regulation and Regulatory Intent*

The federal Clean Water Act utilizes two approaches to managing water quality: technology-based requirements and national water quality standards. Section 303(d) of the Act integrates these two approaches by stipulating that states make a list of water bodies that are not attaining standards after the technology-based rules are implemented. For water bodies on this list, as well as where the U.S. Environmental Protection Agency (EPA) Administrator believes appropriate, the states are to formulate TMDLs which must account for all sources of the contaminants that forced the listing of the water bodies. Under federal law, TMDLs must account for contributions from point sources (federally permitted discharges) and pollution from nonpoint sources. The U.S. EPA must review and approve the list of contaminated waters and every TMDL. In the event that the U.S. EPA does not approve the list of impaired water bodies or a TMDL, the Agency must establish them for the state. (www.swrcb.ca.gov/tmdl/background.html, July 15, 2003)

The Clean Water Act does not specifically require the adoption of TMDLs. Instead, Section 303(d), Section 303(e), and their provisions stipulate TMDLs be included in water quality plans. The U.S. EPA has adopted rules (40 CFR 122) requiring that the National Pollutant Discharge Elimination System (NPDES) permits be modified to be consistent with all approved TMDLs. An NPDES permit outlines specific limits of pollution for a particular discharger. Nearly all the states, including California, are permitted to administer the NPDES permit program. (U.S. EPA administers the permit system in the remaining states.) Implementation plans are to be formulated along with the TMDLs.

*California Law*

California effectuates the provisions under the Clean Water Act principally through institutions and procedures set out in certain provisions of the California Water Code, including those of the California Porter-Cologne Water Quality Control Act. These provisions established the State Water Resources Control Board (SWRCB) within the California Environmental Protection Agency to develop and implement state policy for water quality control.

The Porter-Cologne Act also established nine California Regional Water Quality Control Boards that operate under the authority of the SWRCB. Each Regional Board is comprised of nine members and an executive officer appointed by the members of each board. The Regional Boards develop and adopt water quality control plans for all areas within their region. The SWRCB formulates, adopts, and revises general procedures for the development, adoption, and execution of water quality plans by the Regional Boards. It reviews these plans and either approves them or returns them for revision and resubmission. Water quality plans do not become effective until the SWRCB endorses the plans, followed by approval by the California Office of Administrative Law.

*The Evolution of Water Pollution Control*

During the 1970s, policymakers considered point source pollution to be the biggest threat to the water quality of the nation's inland lakes, rivers, and streams. (www.swrcb.ca.gov/tmdl/background.html, July 15, 2003) The Clean Water Act established a number of programs to address point sources of pollution, and most federal money went to formulate and implement point source controls. California pursued the same approach in its effort to improve the state's water quality. In addition, the State and

Regional Boards implement smaller scale corrective actions for nonpoint source pollution as permitted under the Porter-Cologne Act.

A major goal of the Clean Water Act was to expand treatment of wastewaters. According to Rosenbaum (2002), all treatment plants in operation before July 1, 1977 were required to have "secondary treatment" levels. All treatment facilities, regardless of age, were required to have "the best practicable treatment technology" by July 1, 1983. The Act also appropriated 18 billion dollars between 1973 and 1975 to assist local communities in building necessary wastewater treatment facilities. The federal government paid for 75 percent of the capital cost for building the new facilities. Programs focusing on treatment facilities resulted in significant improvements in water quality by the late 1980s.

Concerns over the nation's water quality arose again due to the growing impacts of nonpoint source pollution, and environmental groups looked to the TMDL requirements to ameliorate continuing water quality problems. A series of lawsuits ensued to force regulators to adopt an aggressive approach to TMDL development. Thus far, over 40 lawsuits have been filed throughout the nation, most of them by environmental groups. (www.swrcb.ca.gov/tmdl/background.html, July 15, 2003) The lawsuits are commonly filed against the U.S. EPA due to its responsibility to approve TMDLs. Several of them have led to negotiated settlements and consent decrees that are overseen by the courts. At present, California is operating under three consent decrees covering most of the North Coast Region, the entire Los Angeles Region, and Newport Bay and its tributaries in the Santa Ana Region.

TMDLs in California are established either by the Regional Boards or by the U.S. EPA. Those established by the Regional Boards are designed as Basin Plan amendments and include implementation rules. Those formulated by the U.S. EPA normally contain the total waste load allocations as required by Section 303(d), but do not include extensive implementation rules, primarily because U.S. EPA implementation of nonpoint source pollution control strategies are generally confined to education and outreach in accordance with CWA Section 319. (www.swrcb.ca.gov/tmdl/background.html, July 15, 2003) Presently, TMDLs are required for all waters and pollutants on the 303(d) list and must consider and include allocations to both point sources and nonpoint sources of contaminants. The limitations in a TMDL may be other than "daily load" limits. There also can be multiple TMDLs on a specific body of water, or there can be one TMDL that focuses on many contaminants. Current examples of TMDLs in the Los Angeles Region include the trash TMDLs for the Ballona Creek and Wetland, Los Angeles River Watershed, and East Fork San Gabriel River, and the wet-weather bacteria TMDL for the Santa Monica Bay Beaches. At this time the Section 303(d) list contains over 1,400 water body/pollutant combinations. Based on this list, the State Board estimates that about 800 TMDLs are needed. The Regional Boards are now developing over 120 TMDLs, with several addressing multiple pollutants. (www.swrcb.ca.gov/tmdl/background.html, July 15, 2003)

Concerns over implementation have become a significant issue in the formulation of TMDLs. (www.swrcb.ca.gov/tmdl/background.html, July 15, 2003) Although these concerns generally fall outside the provisions of Section 303(d), they are nevertheless important to achieving water quality improvements as a result of the establishment of TMDLs. While it is possible to conduct technical assessments of total load without considering implementation issues, one must address the possible mechanisms by which pollution can be reduced in determining allocations to various sources. Considering different implementation options can help analysts avoid adopting allocation schemes that are far more costly than necessary or, even worse, unachievable. The TMDL strategy in California seeks to engage the public and cultivate an understanding of watershed issues. It relies on an adaptive process that matches management capabilities with scientific knowledge and information.

*The Stormwater Permit*

The Los Angeles Regional Water Quality Control Board (LA Regional Water Board) has adopted a NPDES permit containing waste discharge requirements for MS4 discharges within the County of Los Angeles (with the City of Long Beach excluded because it is covered under a separate MS4 permit). The main intent of the Permit is to reduce significantly the amount of various pollutants contained in stormwater runoff. The County of Los Angeles has identified seven critical industrial and commercial sources of contamination: 1. wholesale trade (scrap recycling, automobile dismantling), 2. automotive repair/parking, 3. fabricated metal products, 4. motor freight, 5. chemical and allied products, 6. automotive dealers/gasoline stations, and 7. primary metal products. The priority industrial sectors and automobile repair facilities/ gas stations (two of the commercial sectors) on the list contribute substantial concentrations of heavy metals to stormwater. Overall, the Permit is intended to establish and implement a timely, comprehensive, cost-effective stormwater pollution control program to reduce the discharge of pollutants in stormwater to the Maximum Extent Practicable (MEP) from the permitted regions in the County of Los Angeles to the waters of the U.S. subject to the jurisdiction of the Permittees and also meet water quality standards. BMPs must be identified and implemented to reduce the discharge of pollutants in stormwater to the MEP and also meet water quality standards.

The Permit has established an iterative process that allows municipalities in Los Angeles County to measure noncompliance, test alternative BMPs, and consult County and regional water quality authorities. Thus, the Permit provides a mechanism to make adjustments to the required BMPs as necessary to ensure their adequate performance. According to the U.S. EPA, "Water quality-based effluent limits for NPDES-regulated stormwater discharges that implement wasteload allocations in TMDLs *may* be expressed in the form of BMPs under specified circumstances....If BMPs alone adequately implement wasteload allocations, then additional controls are not necessary." (U.S. EPA, Memorandum, November 22, 2002, p.2)

**Regulatory Mechanisms**

Pollution control regulations can range from programs that prescribe very specifically what the regulated community is to do, to programs that only set goals and leave the community to find the best methods to reach the goals. Programs of the first kind are often criticized by the regulated community for lack of flexibility—the standard complaint is "This approach does not work well for our particular case. We could do this in another way and accomplish the goals for a lower price". Programs of the second kind provide flexibility, but are often criticized for vagueness: "We don't know how to do this. We are not sure what we have to do to come into compliance".

The stormwater management program is clearly of the second type, and it should be so. Stormwater quality control is an extremely complex issue, influencing, if not everything under the sun, then everything under the rain. The best means of compliance will certainly differ from city to city, depending on land uses, land prices, and a host of physical characteristics of the landscape. It is likely that, as the nation engages the problem, new approaches will be developed. Entrepreneurs will develop new devices and methods as others are tried and discarded. Strict specification of methods at this time might well eliminate approaches that are more economical and effective, so a flexible approach is best.

However, an inevitable side effect of maintaining flexibility is that the regulated community faces an unsettling level of uncertainty. Mayors and city councils faced with planning future infrastructure and future budgets are understandably uncomfortable facing mandatory water quality goals without specified means of reaching those goals. This level of uncertainty will decline as plans are developed and experience with water quality control measures accumulates.

There is a historical precedent for this approach in the program for control of air pollution in Southern California. Like stormwater pollution, it is generated by a very large number of sources with varying compositions and emissions rates. Many of the sources are difficult to monitor and regulate. Implementation of pollution controls has been accompanied by intense political controversy. Even so, air pollution control efforts have been relatively successful—pollution levels and their associated health effects have declined. While costs have been high and some high-polluting marginally profitable businesses have closed or left the area, it is also clearly true that the economy of the area has not collapsed, as some predicted. Few people would suggest that we should return to days when taking a deep breath was literally painful.

**Policy Implementation**

Our research indicates that the LA Regional Water Board is strongly committed to abating pollution from stormwater runoff as effectively and inexpensively as possible. The U.S. EPA supports the LA Regional Water Board's efforts to require individual municipalities in Los Angeles County to adopt necessary BMPs to control stormwater runoff. Federal and state policymakers along with environmental group leaders believe that BMPs, if widely and strategically implemented, can significantly reduce stormwater pollution and improve water quality throughout Los Angeles County. Given the proven effectiveness of BMPs in different areas of the country (and the world), the LA Regional Water Board does not envision the need to build new advanced treatment plants throughout the region, and indeed has expressed the specific intent that such plants should not be required. Advanced treatment is viewed as an absolute last resort given the huge expense it would entail and the confidence policymakers and environmental leaders have in the ability of BMPs to reduce pollution significantly and allow the region to meet federal clean water standards. The authors of this report concur with this position. Some municipal leaders in Los Angeles County have asked why they should be forced to adopt BMPs when there is a possibility that advanced wastewater treatment plants will ultimately be required. Even if advanced treatment plants are necessary in the future, which is highly unlikely, the adoption of BMPs will dramatically reduce the amount of water and the mass of pollutants these plants will treat. This will reduce pollution treatment costs and improve the effectiveness and ability of plants to handle large volumes of water during heavy rain periods. That is, BMPs will be used as part of any program to build advanced treatment plants because the much cheaper BMPs will reduce the costs of the very expensive advanced treatment plants. Implementing BMPs now will be a good investment even in the unlikely event that an advanced treatment plant is required.

The LA Regional Water Board has focused some efforts on reducing trash in stormwater runoff, and it has adopted a "zero trash" rule to achieve this goal. The Board does not expect all communities to eliminate every single piece of trash from inclusion in stormwater runoff. Instead, the Board policy is that communities in Los Angeles County make reasonable efforts to prevent trash from entering storm drains. "Trash" is defined as materials larger than ½ cm, so municipalities can comply with this regulation by installing ½-cm screening devices on their catch basins, by enforcing litter laws already on the books and by conducting street sweeping in areas where trash tends to accumulate. Public education about littering and the installation and maintenance of catch basin devices can provide substantial progress in preventing garbage from entering storm drains.

In order to avoid a costly court battle with state water pollution policymakers, the County and City of Los Angeles have recently agreed to spend $168 million to reduce by half the amount of trash that collects in the 51-mile-long Los Angeles River (McGreevy and Weiss, 2003). In addition, the City of Los Angeles agreed to drop its lawsuit against state policymakers over the overall plan to abate polluted stormwater runoff. The agreement settles a lawsuit filed by the city and county that opposed the LA Regional Water Board's requirement to reduce trash entering the river 10 percent annually over the next 10 years. The LA Regional Water Board officials negotiated the deal, which requires the city and county to reduce rubbish going into the river and Ballona Creek 50 percent by September 2008, at which point state regulators will consider whether further rules are necessary. The agreement also provides local officials more flexibility in trying less-costly approaches of reducing trash. Environmental groups such as Heal the Bay, Santa Monica BayKeeper, and Friends of the L.A. River applauded the agreement. Rather than spend money on litigation, county and city officials will allocate funds to improve water quality.

Clearly, all communities in Los Angeles County will have to share the financial burden in helping to reduce contamination from stormwater runoff. This may require many communities to modify their budget priorities.

As long as communities make a reasonable, good faith effort to address stormwater pollution issues, it is unlikely that federal and state officials will take legal action. Thus far, this has been the case. Failure to make such an effort, however, will certainly result in legal action against violators. Moreover, environmental groups can choose to file lawsuits against federal and state officials if they do not continue to pursue polluters. Such action will lead to costly delays in meeting federal water quality standards and will likely lead to even more draconian measures given present federal and state law and previous judicial decisions.

**Previous Actions by the LA Regional Water Board**

The impacts on water quality and the heightened risks to public health from MS4 discharges that affect receiving waters across the U.S. and in Los Angeles County and its coastline have been well studied and documented. Accordingly, the LA Regional Water Board has taken a number of significant actions to control such discharges (LARWQCB, 2001)

In 1990, the LA Regional Water Board adopted Order No. 90-079, the Los Angeles County MS4 Permit. That permit required the Los Angeles County Flood Control District, the County of Los Angeles, and the incorporated municipalities in Los Angeles County to implement stormwater pollution controls including updating ordinances, optimizing existing pollutant controls such as street sweeping, construction site controls, and others. The Regional Board required all Permittees to adopt at least 13 specific BMPs for consistency across the County. The 1990 permit was executed on a system wide basis due to the highly interconnected storm drain system serving a population substantially larger than 100,000 residents. At this point, the region was committed to MEP standards—cleaning up stormwater to the maximum extent practicable.

On July 15, 1996 the LA Regional Water Board issued Order No. 96-054 that updated the 1990 permit. The 1996 Los Angeles County MS4 permit required model programs be formulated and implemented by the Permittees for Public Information and Public Participation, Industrial/Commercial Activities, Development Construction, Illicit Connections and Illicit Discharges, Public Agency Activities, and Development Planning. These model programs will change with time as more data on stormwater impacts are collected and become available.

On January 31, 2001 the Los Angeles County Department of Public Works formerly requested to renew their MS4 permit in the form of an ROWD for the County of Los Angeles and the incorporated cities, except the City of Long Beach. This request began the process of reissuance of the permit, which entered into its third permit term. On the same day the Los Angeles County Flood Control District submitted an ROWD. The Regional Board staff invested considerable time and effort in providing opportunities for public participation and comment. Over 30 meetings, two workshops, and many outreach activities were conducted to allow the public, Permittees, and other interested parties enough opportunity to participate in the development of permit requirements and language prior to consideration by the Regional Board for adoption. The reissued MS4 permit committed the region to meeting water quality standards based on the State Water Resources Control Board's precedential Orders.

Implementation of the MS4 permit requirements should reduce pollutants in stormwater in a cost-effective manner. The adoption of BMPs should also reduce pollutant discharges and enhance the quality of surface water.

The final steps of the regulatory process are now under way—TMDLs for the various impaired water bodies of the region are being promulgated.

Overall, it is clear that the LA Regional Water Board does not intend to require that municipalities build advanced treatment plants: indeed, they have publicly expressed the sentiment that they oppose this solution.

**Implementation of Regional Solutions**

A regional infiltration and BMP treatment system, in combination with source control of trash, pesticides, and trace metals, can substitute for individual site controls on land parcels within the drainage area. This could take the form of "Local Equivalent Area Drainages", implementing regional solutions that would achieve better results than the application of new source controls, which, in built up areas, will have significant effects only over the long term during which existing structures are rebuilt.

Funding for regional solutions may pose a challenge because of Proposition 13 and other restrictions on tax policy. The challenge however is not insurmountable if property-owners and voters become adequately informed and educated. Nevertheless, regional solutions may significantly shift administrative and cost burdens for water quality protection from businesses and development firms to local government.

**Trading Schemes**

"Cap and trade" systems, in which regulatory agencies set a cap on the amount of pollution allowable and allow trading of discharge rights within the constraints of the cap, have been successful in several fields. A group of municipalities, for example, might assign discharge rights to landowners within a watershed such that total releases meet the constraints of the TMDLs. They could then allow trading in the discharge rights, so that those who can reduce discharges at least cost are the first to do so, and the overall cost of meeting the TMDL is minimized. Municipalities themselves, as owners of parks and open space, might be able to develop regional solutions and fund them through sales of discharge rights to others.

Stormwater pollution control may be particularly amenable to this approach because the costs of control are highly site-specific. In many cases, there may be considerable economy in applying regional solutions in the best possible sites rather than controlling every site individually.

## DESCRIPTION OF ALTERNATIVE APPROACHES

### Infiltration

Before the City of Los Angeles was established, most of the rain that fell in the region evaporated or percolated into the soil. The groundwater was continually replenished and runoff flows were small. As population grew, impermeable surfaces such as paved roads, parking lots, and rooftops covered more and more of the land. Residences, commercial facilities, and roads were designed to shed water as rapidly as possible. Historical measurements of discharges to the Los Angeles River at Firestone Boulevard indicate that runoff has increased from 5% to 45% of rainfall. This change adversely affected stormwater quality in two ways. First it increased the amount of stormwater flow, magnifying the cost of any measures to control quality (and also requiring ever more costly flood control measures). Second, water that flowed directly to streams and the ocean no longer benefited from the purifying action of soil and vegetation, which can remove particulates through physical filtering, sequester some chemicals by adsorption, and destroy organic and biological contaminants by biodegradation.

Any program for remediation of stormwater contamination should reverse this trend, reducing the load of both water and pollutants on other parts of the system. At the same time, pollution of groundwater must be avoided. However, infiltration will benefit from the very considerable capacity of soils to filter particles, adsorb contaminants, and biodegrade organic materials. A relative estimate of the magnitude of the problem may be made by comparison with examples of leaking underground storage tanks at gasoline stations. In many cases, spills of tens or hundreds of gallons of gasoline are now being handled by "intrinsic remediation"—allowing natural biodegradation to degrade the hydrocarbons. The acceptability of this approach has been supported by extensive research. Hydrocarbon infiltration with stormwater will involve far lower concentrations of hydrocarbon, and will mostly be the higher-molecular-weight compounds that are much less mobile in soils than gasoline.

We can also compare stormwater infiltration to the effects of septic tanks. These systems infiltrate sewage that has received only a modest degree of treatment. Yet they are still in use in the Los Angeles Region, and indeed are the primary waste disposal method for 15% of households in the U.S. Groundwater contamination from septic tanks has occurred, but most are considered effective and safe waste disposal systems.

This comparison suggests that the relatively low concentrations of pollutants in common stormwater, with appropriate controls on sources of specific contaminants, will not pose a significant threat to groundwater quality.

The permeability of soils in the Los Angeles basin varies from place to place. Beneath the Whittier Narrows spreading basins, for example, sand and gravel deposits allow very high rates of infiltration. In other areas, clay-rich soils reduce rates of infiltration. However, the historically low rates of runoff indicate that infiltration is capable of handling the bulk of the rainfall in the Los Angeles Region. Many areas routinely considered as having poor infiltration rates will never the less be useful as multi-purpose infiltration systems. A soccer field, for example, can be used as an infiltration basin at little additional cost, and will make a valuable contribution even if infiltration rates are low in comparison to those in spreading basins.

**Source Control**

*Industrial Releases*

Industrial discharges can be controlled by a vigorous program of source identification and control. Businesses have a fundamental responsibility to do their work without contaminating their neighborhoods, and in the great majority of cases can do so without significant interference with their activities.

*Trash Management*

Many businesses and some homeowners contribute a disproportionate amount of trash to the urban burden. Paper waste often accumulates in the parking lots of fast food outlets and strip malls, where it can wash into the street during rainstorms. Inadequate dumpsters and garbage cans are overloaded so that trash spills into the streets. Poorly covered trucks can allow trash to fly out on the streets. In addition, citizens throw trash from their cars onto the streets (it has been estimated that as much as 60% of trash on freeways by weight is cigarette butts). All of these practices are illegal, but enforcement is currently rare and weak. While perfect compliance with anti-litter laws is not expected, there could certainly be major improvements through enforcement. Much of the cost of such efforts could be recovered through fines, with the satisfying result that those causing the problem would be paying for cleaning it up.

Municipalities are responsible for the trash deposited on their streets, and most will respond by installing screens on catch basins. These are sometimes referred to as catch basin "inserts". They will have half-centimeter openings and will be designed to collect trash during periods of low or modest flow, but to bypass the flow during heavy storms or if they are clogged. This will avoid local flooding that would be caused by clogging.

*Street Cleaning*

Trash that escapes enforcement efforts can be collected by street cleaning before it reaches the storm drains. Enhanced street cleaning is likely to be necessary as cities install half-centimeter screens on their catch basins. Trash that is now washed out of sight (at least until it reaches the beaches) will accumulate on the screens and possibly clog them. More effective and more frequent street cleaning will reduce this problem.

A major fraction of the pollutants in stormwater runoff are adsorbed on particles—this is particularly true of trace metals and pesticides, which are significant contributors to impairment of the receiving waters. Some of this particulate matter can be removed from streets by higher-quality street vacuuming equipment, which collects the dirt much as a vacuum cleaner does. This equipment is more expensive to purchase and operate, but it would make a significant contribution to reducing chemical pollutants in stormwater.

The Port of Seattle has tested high-quality street sweepers as a cleanup method in its container storage area (FHWA, 2003). The approach was successful, removing one-third to one-half of particulates and their associated pollutants. While the equipment is somewhat more expensive than simple sweepers to purchase, operations costs are about the same. The fine particles carry a significant portion of the pollutants, but they constitute only a small portion of the total mass of material on the streets, so their collection and disposal does not significantly increase costs. Such street cleaning may be more effective in Southern California, where the long dry season allows dust to accumulate for many months.

As explained in detail later, there would be substantial secondary benefits associated with improved street cleaning. Neighborhoods would look better, and residents would be exposed to less resuspended road dust, which dirties buildings and may have significant negative health effects.

Some investigators have also proposed street washing, using recycled water. If this were done during dry weather, and all of the dry-weather flow were being collected for treatment in wastewater treatment plants, street pollutants would be kept out of the rivers.

*Pesticide Substitutions*

Many of the receiving waters in the Los Angeles Region are impaired by pesticides, particularly Diazinon and Chlorpyrifos. The approach to this pollution should be the same as it has been historically for other pesticides that threatened environmental quality. None has ever been dealt with by treating contaminated waters. Those who use the pesticides should be responsible for ensuring that no water pollution results from that use. Pesticides that cannot be properly managed by appropriate use protocols such as labeling or use rules enforcement and which have an inherent tendency to persist in the environment should be banned. Pesticide controls are instituted by the state and federal governments, so additional political effort will be needed if a bans on specific compounds are required.

We presume that these pesticides are used in many cases because they are currently the most economical approach to insect control, and that substitution of another method would involve some cost. However, there are many possible alternatives, including use of more readily degraded pesticides, insect-resistant strains of plants, biological control with natural insect predators, and others. There are many examples of success with such integrated pest management (IPM), particularly at golf courses (NRDC, 1999). In some cases owners were pleased to find that costs actually declined when they switched from pesticide-dominated approaches to IPM.

*Trace Metals*

Trace metals enter stormwater as rain drains from industrial operations, transportation land uses, and other sources. Brake pad wear on cars produces a fine dust of copper. Zinc is released when galvanized equipment contacts the water. Trace metals in stormwater can be controlled by covering machinery and materials that release trace metals, by capturing and treating runoff from large industrial operations and transportation land uses, and by developing alternative materials for brake pads (research is currently under way on this objective).

*Control of Automotive-Related Sources*

Motor vehicles and related facilities are the source of many types of runoff pollutants, including hydrocarbons from oil and fuel leaks, and road wear. Vacuum street cleaning is effective in dealing with particle-bound hydrocarbons left on the street, and infiltration can effectively deal with hydrocarbons that are transported or deposited off the street surface.

*Control of Bacteria*

Bacterial contamination in stormwater is typically measured as counts of "coliform" bacteria, a category that contains many species of bacteria. While very few of the coliforms cause disease, some of these species are very abundant in human waste, and so detection of the group has long been used as a marker for sewage pollution. Efforts to interrupt the fecal-oral transmission of disease have commonly taken the elimination of coliforms from water as a surrogate for judging efforts to prevent the spread of the microorganisms that do cause disease. Where coliform counts in drinking water have been reduced (in much of the industrialized world) transmission of water-borne disease has indeed been largely eliminated. Thus the use of coliform counts as a marker for disease control has been remarkably successful. In some cases, a more specific test for "fecal coliforms" is used, because the test is an indicator of contamination by warm-blooded animals, including humans. While we have always counted coliforms, the real concern is pathogens—microorganisms that can cause disease. For sewage pollution, the association between the two has been strong, and controlling coliforms has been equivalent to controlling disease. The situation for stormwater, however, may be far more complex. Because there are many non-human sources of coliforms, it is possible that the test for their presence may be positive even when no human pathogens are present.

The sources of the coliforms found in stormwater remain uncertain. Pet wastes certainly include bacteria that test positive as coliforms, but the degree to which pet wastes constitute a disease threat is uncertain. Wild mammals, such as raccoons, possums, skunks and coyotes, may contribute when their wastes are left on paved surfaces. It has been proposed that fecal matter from homeless people denied access to restrooms may be a source, but there has been no study confirming this. In less developed areas with poor soil infiltration conditions, it is likely that poorly operated septic tanks and illegal disposal of gray water are contributing to the coliform counts detected in runoff. If septic tanks are the source, strict enforcement of waste control ordinances is appropriate. If homeless people are the source, provision of restroom facilities would be far cheaper than any imaginable stormwater treatment system (as well as being more humane). If pet feces are the source, the only approach is, through public outreach and enforcement, to press people to clean up after their pets. It must be expected, however, that such an approach will not be 100% effective. The contribution of wild animals seems uncontrollable.

Because the sources and significance of the coliform counts remain uncertain, it is important that research on the topic be pursued immediately. The recent development of genetic techniques for precise and rapid identification of bacterial species now provides the tool needed to provide the information needed to develop effective policies.

Coliforms, and presumably the associated human pathogens, are substantially reduced in treatment wetlands. Infiltration of course removes them from runoff flows, and adsorption on soils and biodegradation are effective at protecting groundwater. Water storage, because it holds coliforms in an environment for which they are not adapted, and because it allows settling of particles to which they may be attached, has some beneficial effect. Disinfection, using chlorine, chloramines, or ultraviolet light is possible, but relatively expensive.

Water Quality Control Board Rules allow for 17 exceedences of the coliform limit per year. There are about 32 days per year of significant rainfall in the region, so it has been anticipated that exceedences during the heavy winter storms will be difficult to control, and will be allowed.

**Improved Enforcement**

It is important that source control efforts include genuine and credible enforcement. Rules that are widely ignored, of course, will not help clean up runoff water, and a considerable fraction of runoff contaminants come from illicit discharges or disposal. Trash is an obvious example—littering is already illegal, so 100% of the trash in stormwater represents illegal release.

The Environmental Protection agency describes an example in which improved enforcement of existing law was effective (USEPA, 1999):

"...during a 12-month period, the Houston, Texas, Public Utilities Department identified 132 sources of discharges leading to Buffalo Bayou, the local drinking water source, with estimated flow rates ranging from 0.3 to 31.5 liters per second. Houston's program involved monthly sampling from bridge crossings; analysis of samples for carbonaceous biochemical oxygen demand, ammonia and nitrate nitrogen, pH, TSS, DO, temperature, fecal coliform, and chlorine residual; comparison of samples to baseline flow concentrations; weekly sampling of temperature, dissolved oxygen (DO), and fecal coliform in stream reaches suspected of contamination; boat sampling to identify the contaminating outfalls along the reach; and, finally, a land-based search to pinpoint the source. Of the flows identified during the program, 85% were due to broken or clogged wastewater lines and 10% were due to illicit connections (Glanton et al., 1992). Eight months after an illicit discharge detection and elimination program began, fecal bacteria log mean concentration was reduced from 20,000 colonies/100mL to 2,000 colonies/100ml."

Thus, in this example, a 90% reduction in bacterial contamination resulted from a careful enforcement program alone.

**Detention and BMP Treatment**

*Stormwater Detention Basins*

Many of the problems of stormwater management are associated with its very irregular rate of flow. During dry periods runoff flow rates are so low that the water can be handled by existing sanitary wastewater treatment systems. During rainstorms, the water comes so fast that municipalities have had difficulty doing anything beyond avoiding floods.

The first step toward dealing with this problem is to increase infiltration—substantial reductions in the peak flow rates are possible. The second approach is to provide storage systems that will hold water back during the peak flow periods. Detention basins will reduce peak flows, collect trash, provide quiet water for settlement of particles and their associated pollutants, and promote infiltration. Analysis of the

National BMP Database (Strecker et al., 2003) shows that detention basins infiltrate an average of 30% of the water they receive.

The primary difficulty with this approach is the shortage of available sites to construct large reservoirs. The topography of the Los Angeles area does not include any deep canyons in lower reaches of the rivers that could easily be made into reservoirs. Moreover, virtually all of the land is already occupied by other uses and would accordingly be very expensive to acquire.

This means that detention basins must be conceived as a distributed network of smaller systems, with each serving multiple uses. A useful model is the Sepulveda Dam Recreational Area, which retains water during storms to prevent downstream flooding. For the great majority of the days in the year, the basin is mostly empty, and serves as a park and a wildlife refuge.

A rough estimate of the general feasibility of a regional-park-based approach can be calculated. The City of Los Angeles currently has about 5% of its area in parks (Wolch et al., 2002) and it is reasonable to presume that at least a similar fraction is park throughout the LA Region. Thus, moving the rainfall from adjacent developed areas to the parks would constitute concentration of the flow by a factor of 20 (20 acres of land would drain to 1 acre of park).. If the runoff coefficient for the developed areas is 0.5, a rainfall of ¾ inch would thus put 8 inches of water in the parks. This is less than the 24-inch depth of flooding assumed for the stormwater parks planned in the Sun Valley project, suggesting that this approach is feasible on the large scale in terms of the amount of land required.

This calculation is quite approximate: the runoff coefficient is uncertain, and several other factors are poorly known. Never the less, the calculation suggests that a joint program could simultaneously provide the region with needed parks and needed stormwater infiltration capacity.

*Sanitary Treatment of Dry Weather Flows*

During dry weather, small flows are present in the stormwater system as a result of overwatering of lawns, car washing, and other discharges. This modest amount of water can be collected and passed through existing wastewater treatment plants, which commonly have more than enough excess capacity for this purpose. Because the dry season in Southern California is very long, this would prevent runoff pollution of the oceans for much of the year.

Where this is done, street washing with recycled water would be possible. Collecting and treating the contaminants during dry periods would leave the streets clean for the rainstorms, when the water cannot be collected.

*Treatment Wetlands*

Wetlands remove many pollutants from the water that passes through them. The low flow velocities allow sediments to settle, removing particulates and any pollutants that are adsorbed on them. Algae and rooted plants absorb nitrate and phosphate as they grow. Vigorous microbiological activity degrades organic chemicals, as microbial predators consume disease organisms. These observations suggest that wetlands can be constructed to serve as treatment systems for stormwater and dry weather runoff. While this approach requires dedication of land, it has the considerable secondary benefit of providing riparian wildlife habitat and esthetic values.

A system of treatment wetlands has been designed for the San Diego Creek Watershed that drains to Newport Bay, in Orange County, California. The system will serve an area of 120 square miles, and is expected to cost in the low tens of millions of dollars. It is expected to meet the low-flow nitrogen TMDL, the phosphorus TMDL during most years, and the fecal coliform TMDL during low flows.

A similar system has been constructed to provide stormwater quality protection for the Ballona Wetlands Watershed in the City of Los Angeles.

*BMP Treatment of Flows from Problem Watersheds such as Industrial Areas*

If source control is not successful for some industrial areas, it may be necessary to collect the runoff water and use more sophisticated BMP treatment. These might best be constructed as private facilities serving a consortium of local industries, and funded by them for the purpose. A public/private partnership could be created, perhaps with public loan guarantees. Past experience with business improvement districts could serve as a model.

*Partial Treatment in Curbside Units*

Many proprietary devices have been developed for treatment of runoff as it enters curbside catch basins. These generally remove trash from the flow, and may also collect sediments. Some include adsorbants to remove hydrocarbons and trace metals. They have the disadvantage that they are designed to bypass during higher volume wet-weather flows. All require some degree of maintenance, and some are expensive to install. Trash and sediment must be removed on a regular basis, and adsorbants must be replaced when they are exhausted. Never the less, they may be useful for treatment of problem dry weather flows in specific areas, such as industrial or commercial zones.

**Public Outreach and Education**

Much of the pollution in runoff water arises from actions of individuals—litter is discarded in the street, for example, or pesticides are used carelessly in a residential garden. This pollutant load can be reduced by educating citizens and urging them to behave in a way that protects water quality.

An effort in Oregon, conducted by the Tillamook Bay Rural Clean Water Project, was made to educate local farmers about the steps they could take to protect local streams. This involved personal visits, tours of successful BMPs, newsletters, and presentations (USEPA, 1999). Four years after the program began, bacterial concentrations dropped 40% to 60% in Tillamook Bay and 50% to 80% in local rivers. Thus in some cases significant progress can be made at very low cost through public education.

**Good Housekeeping for Municipal Operations**

While the behavior of individual citizens may be difficult to control, municipalities have far more control over their own operations. Efforts can be made to avoid careless use of pesticides and fertilizers on municipal facilities. Such steps have modest, but measurable impacts. An EPA report notes (USEPA, 1999):

> "…the City of Bellevue, Washington, found that street cleaning three times a week removed about only 10% of urban runoff pollutants; catch basin cleaning

twice a year was estimated to be about 25% effective" (Pitt and Bissonnette, 1984).

**Combined Approaches for Stormwater Quality Management**

A general classification of rainfall receivers and appropriate methods for dealing with runoff they produce is shown in Figure 1. While the approach it describes is quite general, and other mixes of alternatives are possible, it shows one set of measures that can be used to control stormwater pollution.

**Streets**

The first step in reducing pollutants on streets is to restrict pollutant discharges from adjacent properties. Source control measures should prevent the release of industrial pollutants and construction sites should be managed to contain sediments. Litter laws and pet dropping collection laws should be enforced, although it must be acknowledged that it is not possible to prevent these inputs entirely. To stop litter from entering the storm drains, cities should install half-centimeter screens on their catch basins. The use of such screens will require diligent street cleaning, to ensure that the drains are not blocked during storms. In Southern California, rains mostly occur during a well-defined season, and frequently weather reports give two or three days warning of major storms. Cities should develop contingency plans for rapid-response street cleaning when storms are coming, to minimize stormwater contamination and the chances of flooding caused by clogged screens.

In some areas, where runoff water quality is relatively good, the streets themselves might be used as groundwater recharge facilities, by converting unused alleys to park/detention basins or by using permeable pavements.

It remains likely, however, that much street runoff will be of marginal quality. For the immediate future, it is also likely that a major portion of runoff from other sources will be initially discharged to streets, so that efforts to make use of stormwater as a water resource will require collection, and a degree of treatment before infiltration.

In most cases, this can be done with regional solutions. Water from storm drains can be collected in detention basins and wetlands, where sedimentation and biological activity will reduce pollutant load, and groundwater recharge can occur. The detention basins will serve as parks during the greater part of the year when water is not present, and the wetlands will double as much-needed wildlife habitat.

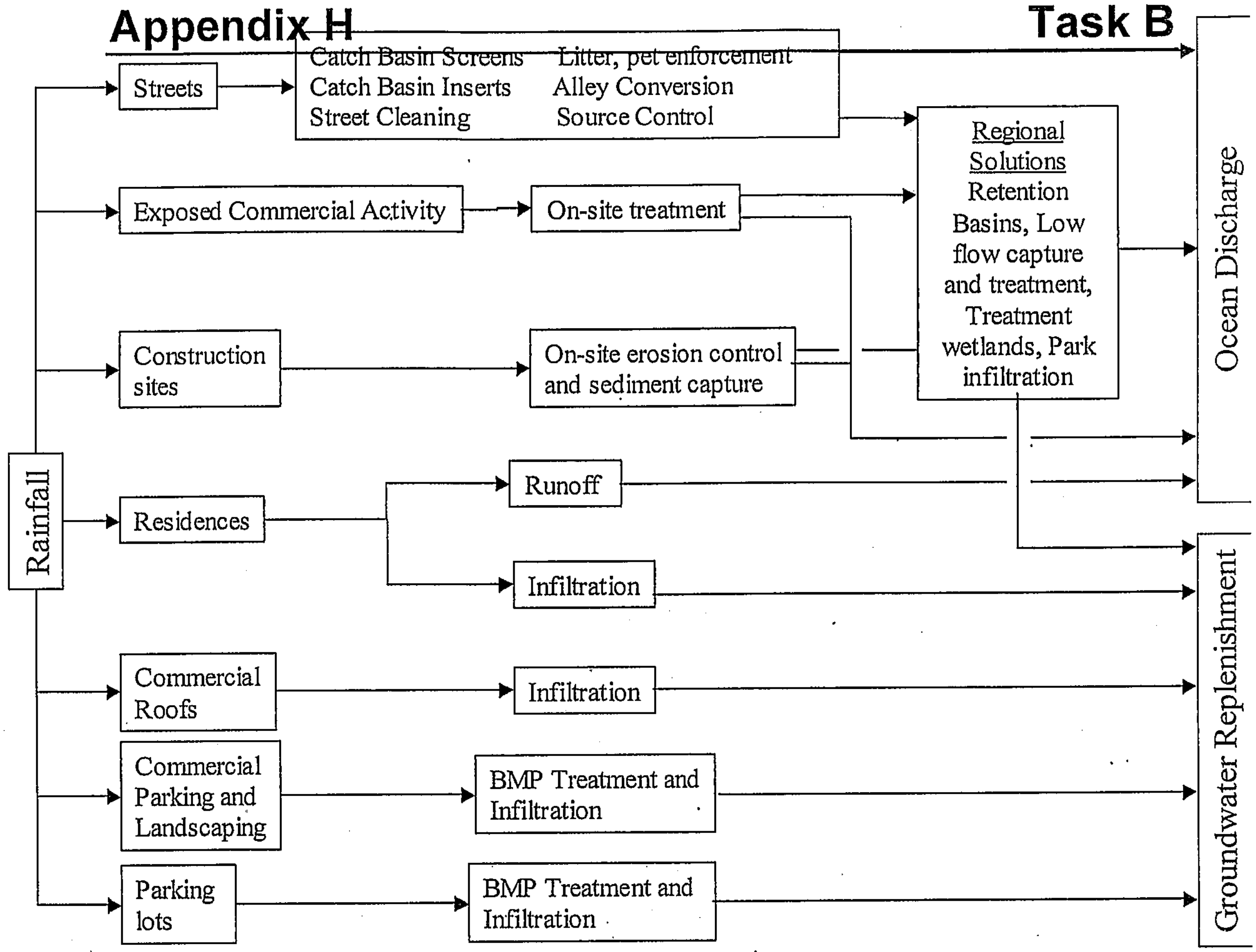


Figure 1. Stormwater quality control solutions for Southern California

### Alleys for Public Use and Infiltration

Some alleys in urban areas are no longer necessary for access purposes. Indeed, many have become nuisance areas because of illicit trash disposal and criminal activity. Many of these could be gated and converted to small parks, with keys provided for local residents. They could simultaneously serve as infiltration facilities or as bioswales. There are currently 2.3 square miles of alleys in Los Angeles, for example. While many must be retained for access purposes, the fraction that could be converted could constitute a significant stormwater retention and infiltration resource. Alleys maintained for access might be candidates for partial or permeable pavements.

Similar approaches could be used for power line rights-of-way.

### Exposed Commercial Activity

Very often the cheapest approach to stormwater quality control for exposed commercial activities is simply to cover them. Stormwater will thereafter come in contact only with the rooftop, and runoff will be much less polluted and more easily dealt with. However, for some large-scale activities, such as oil refining, it is not physically possible to provide a roof. For others, such as auto dismantling, the large area needed and the relatively low value of the activity may mean that a roof is not financially possible. Such facilities must be required to collect and treat runoff from their facilities, and indeed this is already being done in many cases. While there certainly are costs involved, it has generally proven possible, through a combination of better housekeeping, substitution of non-polluting materials, and simple on-site treatment processes, to solve these problems. Requirements for on-site treatment are advantageous because the cost of such treatment is borne by the business that produces the pollutant, providing incentives for conversion to less-polluting products and methods. Consequently, green manufacturing will become increasingly common.

### Construction Sites

Release of sediments from construction sites can be ameliorated if the construction crew provides erosion control measures, such as maintaining vegetation or spraying exposed soil with polymer stabilizers, and an adequate on-site retention pond for rainfall, along with dikes, silt fences, and appropriate vehicle entrance construction to prevent runoff. Detention allows the sediments to settle out and the exposed soils can function effectively for groundwater recharge. It is anticipated that the costs of these measures will be small in comparison to construction costs. A more detailed list of best management practices for construction sites appears in Appendix I.

### Residences

In most cases, homes and the surrounding landscaping have been designed to facilitate rapid runoff. It is necessary that water not pool in depths sufficient to flood houses, and ponding is viewed with irritation, even if it is harmless and temporary. However, single-family homes typically are surrounded with a significant area of land that could serve well for infiltration. Commonly, the land is planted or covered with grass. The runoff from landscaping and residential rooftops typically contains only small amounts of pollutants that are readily removed by percolation through the root zone.

Landscaping for the typical single-family home could be arranged to infiltrate all of the rainfall that it receives (except, perhaps, in the most severe storms). Lawns a few inches below surrounding sidewalks could serve as infiltration ponds, gardens could receive roof runoff, and downspouts could conduct runoff to dry wells. Because the water would have had very little contact with pollutants, such infiltration would be an excellent addition to groundwater resources.

However, very few residences are arranged in this manner and, indeed, building codes often specify features that promote rapid runoff to the street. Building codes should be changed to utilize single-family homes as recharge sites. It is anticipated, however, that the effect on runoff will be seen only slowly in built-up areas as old homes are gradually replaced. Retrofit of existing homes will be expensive and politically difficult, but for new construction, single-family homes could be made to produce essentially zero discharge at little or no additional cost.

Xeriscaping—planting with native and other drought-tolerant plants—can also help to provide space for water infiltration, and it reduces watering and therefore the chance of irrigation runoff. Such landscaping also requires less fertilizer and pesticide, and so reduces incidental contamination.

In many cases, cities may be able to take interim steps to reduce runoff from homes. They have control over the "city strip" land that lies between the sidewalk and the gutter. It would be possible to institute a program of replacing the lawns after minor excavation, so that these areas would lie below the sidewalk and curb and serve as runoff detention and percolation basins.

Where infiltration is not possible, much residential runoff may be acceptable for direct discharge to the ocean, as long as it is not contaminated first by passing through polluted streets. More contaminated water can be conveyed to regional water cleanup and recharge facilities.

**Low-flow Treatment in Wastewater Treatment Plants**

Wastewater treatment plants are built with excess capacity in order to handle increased flow during rainy weather. While sanitary systems are designed to exclude stormwater, holes in manhole covers, leaks in piping, and illegal connections all allow the entry of some water during rainstorms. The flow is a very small portion of the rainwater, but can produce a significant increase in the much smaller sanitary flows—sometimes up to 50%. Treatment plants are designed with excess capacity to handle these peak loads.

This excess capacity can be used to treat dry weather runoff during periods when there is no rain. While these flows are not, by definition, stormwater, and indeed are governed by a separate set of regulations, dry weather runoff is often a significant contributor to impairment of receiving waters and its treatment would contribute to the objectives of stormwater control. It is also possible to use this capacity in concert with "street washing". In this approach, tank trucks filled with recycled water could be used to wash the streets, particularly in the months before the first rain of the fall. Contaminants removed from the streets and drains by the washing would be treated in the wastewater plants, leaving the streets far cleaner when the rains came. At present, municipal street cleaning is a prohibited activity where it results in flows to the storm drain system.

This treatment approach for dry weather runoff could also treat runoff from small rainstorms.

It is likely that all of dry weather runoff could be treated for much of the Los Angeles Region. Such a step would eliminate essentially all runoff pollutants in the areas where this is possible. Because this approach uses capacity that is already in place, the cost for this alternative is low.

This approach would be particularly significant for control of coliforms. Sanitary treatment of dry weather flows would eliminate coliforms through much of the year. Rain occurs during only 32 days of the year, on average (Some of these storms are so small that the runoff could still be treated. On the other hand, untreatably high levels of runoff typically continue for a few days after a major storm). The LA Regional Water Board allows variances for 17 days of wet weather flow during the year. Thus it seems likely that dry weather runoff treatment at wastewater treatment plants, plus some degree of source control, plus the variances, will be sufficient to bring most areas into compliance with the bacteria rules. Further study, including some basic research on the sources of coliforms, is necessary to confirm this.

In considering the acceptability of this approach, it is important to note that beach use declines during wet weather, so that closures during the variance days would have a small effect on overall beach use and public health.

**Capture and Use of Rooftop Runoff**

In many cases, the pollutants from commercial rooftops, like those from residential roofs, could be readily removed by soil infiltration. With appropriate controls to avoid specific pollutants from commercial activities, roof runoff could be used for groundwater recharge. Designs exist for infiltration planters, in which the planter has high sides that allow it to function as a reservoir, and an open bottom that allows infiltrating water to pass into the soil. Risks of groundwater pollution could be mitigated through the use of biologically active and adsorbant soils. Commercial rooftops are commonly associated with large parking areas, which could be adapted for infiltration. Such efforts will be more difficult than those for homes, because most commercial facilities have a higher ratio of roof area to land area. In some cases it may be possible to store runoff for future irrigation use.

The Washington State Department of Ecology (2001) has developed a decision tree for dealing with downspout discharges. For lots larger than 22,000 square feet, it specifies either dispersion or infiltration systems for runoff. For smaller lots on suitable soil, infiltration systems are required. Where soils do not readily accept infiltration, surface dispersion may be appropriate. If water quality is good and infiltration and dispersal are not possible, disposal to the storm drains is accepted.

**Parking Lots and Landscaping**

Parking areas occupy a very large amount of land in Southern California, and accordingly represent a significant opportunity for improvement in stormwater management. Construction costs for parking lots are far smaller per square foot than those for buildings, so that alterations are cheaper. They are reconstructed more frequently, so that requirements applying to new construction or reconstruction will propagate through the parking lot inventory much more rapidly than those for buildings.

In most cases, parking lots could serve as sites for rainwater infiltration. Trash can be collected on grates and be disposed of properly by the lot owners. The curbs around plantings (which are often necessary to avoid damage to the plants from cars) can be slotted so that water passes through them to infiltrate in the planter soils. Planted areas must be below grade, so that they collect and temporarily store water, and could be expanded, utilizing more space where cars don't actually park, such as the areas between and behind the parking bumpers. In some areas, permeable pavements could be used. Collected water could be passed to leach fields built under the parking lot.

An example of this sort of development is provided by the 6-acre parking lot of the Oregon Museum of Science and Industry (NRDC, 1999). It had originally been proposed as a traditional design, with water draining to catch basins, storm drains, and eventually the Willamette River. At the request of the Portland Bureau of Environmental Services, it was redesigned to use vegetated medians and landscaping as swales and linear wetlands. The parking lot is now able to infiltrate the water from a storm of 0.83 inches in 24 hours. Overall construction costs for the revised design were actually lower, because of the reduced costs for catch basins and drains.

Pervious pavements have also been developed so that even the space where cars are parked can be used for infiltration.

There is some concern over whether infiltration from parking lots will pollute underlying aquifers. Sediments, hydrocarbons, and trace metals are likely to be present in parking lot runoff from ordinary commercial establishments. But all of these are generally well retained on soils, particularly if the soils are selected to serve this purpose. Adsorbent materials might be added as a surface layer, to further retain hydrocarbons and trace metals.

It will be necessary to develop new guidelines for parking lots. The public and lot owners will not tolerate flooding that requires them to wade to their cars, so detention and infiltration systems will have to be carefully designed. Overflow will occur in extreme storms, and the lot and remediation areas should be designed so that the excess water flows to the street without impeding access to parked vehicles. Redesigned lots can be required for any new construction or for major renovations, but complete retrofit of all lots is likely to be too expensive for political acceptance.

This will require some additional maintenance. If adsorbants are included in the recharge areas to help control hydrocarbon infiltration, for example, these will have to be renewed from time to time. Regular trash collection will be required.

It is anticipated that most parking lots could become zero runoff areas, contributing substantially to water conservation and pollutant remediation. Further, very large parking lots, such as those at "big box" stores and shopping malls, could be reconstructed as stormwater infiltration facilities serving surrounding neighborhoods. In a cap and trade system, the lots would become financial opportunities for the retailers.

**River Greening**

The Los Angeles Region has become infamous for its historical conversion of rivers to concrete-lined flood control channels. While these have served the purpose of moving water rapidly to the ocean and avoiding flooding, they have also prevented infiltration in the riverbed. For this and many other reasons, advocates have proposed "greening" the river. This would involve widening the river at some points and replacing the steep concrete walls with gently sloping vegetated shores. Parks and wildlife habitat could be developed alongside the river, designed such that they would flood when the river is high. This would allow infiltration to occur, and by providing temporary storage, would decrease peak flood flows. In many areas it may be possible to replace the concrete bottoms of rivers with permeable surfaces.

The Sepulveda Dam Recreation Area is an excellent example of such a facility. It stores water during heavy rains, but serves as a park and wildlife refuge during the greater part of the year when it is not flooded. It promotes infiltration of water during rain events.

Certainly, any such modifications of the rivers must be designed carefully so that flood risk is not increased. But this is clearly possible. Indeed, increased infiltration and storage capacity along the river will reduce peak flows and therefore the frequency of floods, and reduce the associated costs.

**Infiltration in Residential Streets**

Many areas in Southern California are primarily residential, and runoff from these areas is only moderately polluted—it could be used for direct infiltration without treatment. In newly developed areas, homes could be designed so the runoff is near zero. However, many areas are currently already built out. In these, preventing runoff to the street would be expensive. In many cases, it may be possible to install infiltration devices in the public streets.

**Infiltration in Parks**

Public parks, in most cases consisting predominantly of grassy areas, are already contributing to groundwater infiltration. However, some portions still contribute to runoff, and could be regraded to collect water rather than shedding it. Indeed, many could be rebuilt to serve as groundwater infiltration systems serving surrounding areas. Playgrounds could be sunk below surrounding areas in order to collect water during rainfall events. Designs would have to include provision for infiltration at acceptable rates—water left standing for days could become a nuisance. In some areas, soil conditions might preclude this approach.

During the few days after water is collected and before it percolates, that area of the park will be unavailable for other uses. However, parks are little used during rainy weather in any case, and detention will only occur on a few days each year, so the interference will be minimal.

**Public Facilities**

Runoff from public facilities could be reduced by many of the measures previously discussed. Parking lots could be used for infiltration and rooftop runoff could go to planters serving as infiltration systems. Retrofit of government facilities could begin more quickly than for individual homes, as part of the effort required to meet regulations.

## PRIMARY BENEFITS OF RUNOFF QUALITY CONTROL

The immediate purpose of runoff quality control is protection of the receiving waters. In the Los Angeles Region, this refers primarily to rivers, coastal wetlands, bays, and the ocean. Many benefits are definable.

### Fishing

Pollutants in stormwater can adversely affect fishing. Commercial fishing is a small and declining industry in the waters local to Southern California, but sportfishing remains a significant activity, bringing income to coastal businesses and providing recreational opportunity for many people. Cleanup of stormwater will preserve and enhance this activity by ensuring that fish are safe for consumption and by preserving fish breeding grounds in estuaries.

### Swimming

Ocean swimming, as part of a visit to the beach, is a recreational activity enjoyed by millions of people each year in Southern California. It attracts tourists who contribute substantially to coastal economies. It is discouraged if trash litters the beach or if fear of disease discourages water contact. It is prevented entirely in the event of beach closures, which are a common result of polluted stormwater runoff.

### Boating

Powerboats and sailboats are widely used in Southern California and represent a substantial industry in manufacture, maintenance, provision of slips, and various associated shoreside activities. Polluted waters, particularly in the form of trash, can significantly degrade the quality of the boating experience.

### Noncontact Recreation and Nonconsumptive Wildlife Uses

Some recreational activities involve bodies of water without contact: sitting or bicycle riding along rivers or lake shores are examples. These activities are seriously degraded if the water produces bad odors or is littered with trash. A stormwater quality program will protect and enhance these uses.

Observation of wildlife is often a valuable part of the outdoor experience. Continuation of this activity requires water quality sufficient to support birds and animals and the plants and insects that they eat. Many migratory birds are dependent on local bodies of water for their sustenance during their yearly movements.

### Reduced Illness from Contaminated Seafood

Some illnesses are transmitted through consumption of contaminated seafood. Control of the microbiological quality of runoff waters will reduce the extent of such illnesses.

### Reduced Illness from Swimming in Contaminated Waters

Recent studies have indicated that people swimming near storm drains are more likely to contract waterborne diseases than those swimming far from storm drains. Microbiological control of runoff quality, particularly through sanitary treatment of dry weather flows, could reduce the incidence of these diseases.

### Enhanced Esthetic Values

The trash cleanup associated with stormwater quality control will improve the appearance of our harbors, rivers, streets, and commercial establishments. Esthetic enjoyment of wildlife habitats such as wetlands, in particular, is hindered if trash is present.

### Preservation of Natural Ecosystems

Polluted urban runoff damages natural ecosystems in many ways: toxic material can sicken or kill organisms, trash can choke marine mammals or birds, additional turbidity can prevent the penetration of light necessary for seaweed growth, sediment can bury habitats and prevent attachment of organisms to rocky surfaces, and nutrients can fertilize overgrowth of mosses and plankton. This damage can be prevented by stormwater quality control, and is one of the prime reasons for the program.

## SECONDARY BENEFITS OF STORMWATER QUALITY CONTROL

Urban runoff comes from a huge variety of sources and contacts much of the environment around us. The efforts made to clean up runoff, which have the primary purpose of preventing water pollution in receiving waters, will have many secondary benefits and these should be included in any cost-benefit analysis. Indeed, some of these benefits are so substantial that they suggest the agencies responsible for the resources in question should also be providing financial support for runoff quality control efforts.

### Groundwater Restoration

Total rainfall in the Los Angeles basin in an average year is equal to about half of the amount used for drinking water supply. It is strange indeed that we pollute this water and discharge it to the ocean even as we import ecologically, politically, and financially expensive water from the Colorado River, Northern California, and the Owens Valley. The primary difficulty in making productive use of this water is the lack of storage capacity. Rainfalls are infrequent but intense: most of the time there is no rainfall available for use, but occasionally it is so abundant that it causes flooding. Surface water reservoirs are the traditional solution to this problem—water is stored during the rainy season to prevent floods and becomes available for valuable uses the weather is dry. But there are few workable sites for large, year-round surface water reservoirs in the Los Angeles area. Groundwater aquifers, however, can also serve as water reservoirs, being drawn down in the dry season and replenished during the wet season. Infiltration will constitute a use of this storage capacity, reducing future dependence on outside sources of water and avoiding expensive alternatives like desalination of seawater. Because environmental and political factors may make increasing water imports impossible at any price, better utilization of local rainfall through the use of the groundwater reservoirs may be necessary for future growth.

Improvement of groundwater supplies within Southern California would save money now spent on imported water, and would save the concomitant external costs of the environmental impact on source areas. It would also reduce political friction with source areas. Ultimately, it may be the only economically and politically feasible method by which the water supply in Southern California can be increased, and as such, it may be the key to continued development in the area.

### Flood Control

As the fraction of the Los Angeles Region occupied by impermeable surface has increased, the amount of water runoff has also increased, putting an ever-growing load on the flood control system. A recent project improved flood control for the lower Los Angeles River by increasing the height of the dikes on the channels, at a cost of about $200 million. Future increases in channel capacity would be even more expensive—not only will the walls have to be made higher, several bridges will have to be raised. Increased infiltration will reduce runoff, reducing the maintenance costs on the system and eliminating the need for further capacity increases.

The possible magnitude of the impact can be judged by considering the case of the San Gabriel Valley. Runoff from the valley is mostly captured in spreading basins in the Whittier Narrows area and used for groundwater recharge. This makes the runoff coefficient for the valley overall 5%. In the urbanized areas of Los Angeles, the value is about 40%. Thus if the urbanized area were as well controlled as the San Gabriel Valley, runoff could decrease by a factor of eight. Flood risks would essentially disappear.

### Increased Parkland and Wildlife Habitat

The regional alternatives for stormwater quality control include the development of parks and wetlands. The parks would serve as detention basins and infiltration facilities, but would be used for that purpose only during rainy periods, which comprise about 32 days per year in Southern California. During the rest of the year, these areas could serve the typical purposes for which parks are built, acting as recreational sites, playgrounds, soccer and baseball fields, and wildlife habitat. Because people are less likely to engage in these activities during rainstorms in any case, the conflict between the uses will be small. The Los Angeles area is notably short of public parks in comparison to other major cities, particularly in its poorer neighborhoods (Wolch et al., 2002). Because it is likely that residents will demand more park space in the future, the development of areas for dual use is particularly valuable. Ideally, the cost of development could be borne by both agencies intent on improving stormwater quality and by those responsible for parks and recreation. The planned redevelopment of the Corn Fields site in Los Angeles, for example, might provide a detention basin as well as the new park that is being planned.

Wetlands must be kept wet all year, but can withstand flooding during the rainy season. Thus reestablishment of these habitats, which have been largely lost in the Los Angeles Region, could simultaneously serve the purposes of wildlife restoration, flood control, and stormwater quality control. In many cases, it will be possible to develop wetlands within existing channels, reducing the need for additional land purchases.

Some of the parks and wetlands could be created as a part of river greening projects, and so would also serve the purposes of reestablishing esthetically appealing naturalistic rivers.

### Improved Property Values from Trash Control

Often one of the most powerful visual cues that gives a visitor the perception of a "bad" neighborhood is the presence of trash on the streets. One approach to reducing pollutant discharge to storm drains will be improved enforcement of litter laws and additional street cleaning. These will have the secondary benefit of improving the appearance and livability of streets throughout the area. The "broken windows" campaigns of many police departments—indicating that improving the appearance of neighborhoods reduces crime—suggests that apparently cosmetic changes can have substantial benefits for neighborhoods. Certainly property values in a neighborhood with clean streets will be higher than they would if the streets are routinely littered with trash.

### Reduction in Harbor Sedimentation

Sediments carried by runoff are moved because the water moves rapidly, and because small particles remain suspended in the low-salt-content chemical environment of fresh water. When runoff enters bays and harbors, however, the velocity of the water is slowed, allowing the particles to settle to the bottom. The higher salt content of marine waters promotes flocculation of the small particles, so that most of them will also settle to the bottom. The deposited sediment fills channels, blocking the passage of ships and recreational boats, and filling areas set aside for preservation of aquatic ecosystems. Ultimately, harbor dredging is required, and frequently the collected sediment has been contaminated, so that it requires special handling. Dredging associated with storm drains in Los Angeles Harbor, for example, costs between $1 million and $3 million per year. Sedimentation in Upper Newport Bay is considered a significant threat to its function as a wildlife refuge. Stormwater quality control measures would avoid sediments discharges or remove it from the runoff, ameliorating these problems for downstream communities.

**Improved Public Health**

A significant portion of exposure to particulate air pollutants arises when small particles are resuspended from roadways by traffic and wind. Tire dust, settled air pollutant particles, pet feces, particles with adsorbed trace metals and trash are pounded into fine powder and lifted into the air. Such resuspension includes an ultrafine particle fraction, which is most dangerous to human health. More frequent street cleaning, particularly using vacuum bag type cleaners, would reduce public exposure to fine materials carrying trace metals, hydrocarbons, and microorganisms. Some public health improvement is likely, but its magnitude cannot be estimated.

## REGIONAL PROGRAMS DESIGNED FOR STORMWATER QUALITY CONTROL

While there has been a substantial amount of work on individual facilities for runoff quality control, such as detention ponds and grassy swales, there have been only a few studies that have tried to determine the regional cost and effectiveness for a system of these "green solutions". It is important to ask whether it is possible to create an overall program within realistic constraints of land availability and costs that will bring the watershed into compliance with regulations.

We have sought descriptions of example projects that include overall costs and the area of land that drains to the facility, so that cost per square mile of area served can be calculated. In a few cases, these are area-wide systems that are the best evidence that an overall solution is possible. In others, they are single installations, for which we make the assumption that duplication is possible—ten facilities like the one described could be built to serve ten times the area. Because economies of scale are important in determining facility design and even regulatory policy, we have taken special interest in some sources that describe how the size of the drainage area (and the necessary BMP treatment facility) affects cost per square mile. Finally, we have included examples that have actually been built and tested, and others that have only been designed. While data for the latter may be less reliable, most systems perform as designed, and these designed-but-not-built systems provide some of the most useful results.

The chosen examples are described briefly below, and listed in Table 2. Results useful for determining the relationship between facility size and cost per square mile are plotted in Figures 2 and 3.

### Area-Wide Systems

*Sun Valley*

The Sun Valley project was funded by Los Angeles County to develop an alternative approach for flood control and runoff quality management for the Sun Valley district. This is an urbanized area with considerable industrial development that currently does not have storm drains. It is consequently frequently plagued with flooding. The project was undertaken to determine whether there was an approach to flood control other than simply building storm drains.

Four alternative plans were produced, designed to maximize infiltration, to maximize water conservation and wildlife habitat, to maximize stormwater reuse by industry, and emphasizing conveyence to traditional storm drains. Notably, an alternative that maximized the use of onsite BMPs was rejected as too expensive. The components of the plans included industrial reuse, infiltration basins in parks, tree planting and mulching, infiltration in parking lots, and infiltration in vaults beneath the streets.

Because the emphasis of this project was flood control rather than water quality control, the hydraulic control objectives were quite stringent: the system was designed to collect and infiltrate all of the water produced by a 50-year, 96 hour storm. This means that the runoff from the area, if the project is built, will be reduced to near zero. Thus, this project, which includes flood control and water quality control, constitutes an "upper bound" estimate on the costs for water quality control. Achieving such complete collection and infiltration would certainly substantially exceed water quality goals, and costs for a stormwater quality control system in an area with storm drains already in place would certainly be lower.

*San Diego Creek*

A project supported by the Irvine Ranch Water District and Orange County and performed by Geosyntec Consultants has developed a plan for natural treatment systems—wetlands and stormwater detention ponds—for the San Diego Creek watershed. This watershed occupies 120 square miles of developed land that drains into Newport Bay. Newport Bay has been designated as impaired, requiring that stormwater discharges be cleaned up.

Geosyntec proposed a plan consisting of 44 facilities, including ponds and wetlands constructed within existing drainage channels or built outside. These are typically facilities with both deeper open water and shallow water supporting emergent vegetation (such as cattails).

Water quality improvements expected from the system are described in the report (Strecker et al., 2002): "The NTS Plan is estimated to achieve total nitrogen (TN) TMDL for base flows and reduce in-stream TN concentration below current standards at most locations. Total phosphorous TMDL targets would be met in all but the wettest years. The fecal coliform TMDL would be met during the dry season, but not all wet season base flow conditions, and not under storm conditions. The NTS Plan is not designed to meet the sediment TMDL, but would capture, on average, about 1,9000 tons/yr (1,724,000 kg/yr) of sediment from urban areas. The wetlands are estimated to remove 11% of the total copper and lead, and 18% of the total zinc in storm runoff. The NTS provides a cost-effective alternative to routing dry-weather flows to the sanitary treatment system."

While final budget numbers were not provided, it was anticipated that the first 13 treatment sites would be constructed for $12 million, and that the overall cost would be substantially less that the $60 million anticipated for low-flow sanitary treatment. This value is listed as the upper bound of cost in Table 2. For comparison of cost vs. unit drainage area size, it was presumed that the average area served by each of the 44 facilities was 120 $mi^2$/44 = 2.7 $mi^2$.

Constructed wetlands will collect any trash that enters the storm drain, and should be effective at reducing concentrations of coliform organisms, hydrocarbons, particles, and the suite of pollutants associated with particles. They may constitute a complete control system if they are combined with vigorous source control for metals and pesticides and storm drain screens to minimize the trash loading.

*Murray City, Utah, Golf Course and Wetlands*

Officials in Murray City recognized an opportunity when the interstate highway I-215 was being built. They agreed to take soil from the excavation and runoff water from the freeway to make a golf course. The links, with an associated string of settling ponds, accept and treat all of the drain water from the eastbound lanes of 4.5 miles of the freeway (NRDC, 1999; Hill, 2003). The golf course has been a commercial success, and now produces $900,000 in revenue against $450,000 in operating and maintenance costs each year. The city has created other treatment wetlands for essentially all of the runoff from the City and from the westbound lanes of the freeway. The total cost of these wetlands has been less than $1,000,000. Overall, if the golf course infiltration system and the other wetlands are considered as a single stormwater control system, it pays for itself. Because this is an unusual circumstance, for calculation we ignored the income from the golf course, and presume the wetlands cost $1,000,000 and serve the area of Murray City, which is 9.5 mi$^2$.

*Fresno Metropolitan Flood Control District*

The Fresno Metropolitan Flood Control District serves the area including and surrounding the city of Fresno. It operates 130 infiltration basins that drain a region of about 120 square miles devoted to agriculture, residential areas, and urban landscape (NRDC, 1999; Pomaville, 2003). Some of the basins are turfed and serve as parks, while others are bare and serve seasonal infiltration needs. The basins succeed in infiltrating 80% to 90% of the stormwater in their drainage areas, and only 2% enters a receiving water without receiving some degree of treatment. To protect groundwater, the District also instituted a program of industrial inspections. While monitoring is still done to check for pollution of the San Joaquin River, the District anticipates no additional infrastructure will be necessary to meet water quality control regulations. For calculations, the unit area for each basin was assumed to be 1 mi$^2$.

**Individual Systems**

*Long Lake Retrofit, Littleton, Massachusetts*

Geosyntec Consultants also designed a low-impact-development program for Littleton, Massachusetts (Roy et al., 2003). The 1.5-square-mile watershed that contains the town drains into Long Lake, which has been subject to eutrophication and other water quality problems associated with urban runoff. The storm drain system collects water at 200 catch basins and releases it to the lake through 18 outfalls. The plan for mitigation of the problem includes a treatment wetland, grass and vegetated swales, bioretention cells (swales with underdrains), rain gardens, rain barrels, and an outreach program to promote source control for fertilizers.

The total budget for the project is estimated at $630,000, or $420,000 per square mile.

*Tule Pond, Alameda, California*

The Tule Ponds project is a group of three treatment wetlands that was constructed using information developed in the Demonstration Urban Storm Water Treatment Marsh in the early 1980s. It receives urban runoff, passing it through the three ponds in series and discharging it to an existing natural pond. It serves a drainage area of 0.8 square miles and cost $360,000, for a cost of $450,000 per square mile.

*Treasure Island, San Francisco Bay*

Treasure Island is an artificial island of 403 acres in San Francisco Bay that was used for many years as a Navy base. It has recently been converted to residential use. A treatment wetland is planned as the means for stormwater quality control. It is anticipated that wetland construction will cost $800,000 to $ 1,100,000 (Bachand, 2003), or $1.2 million to $1.7 million per square mile. However, the island is a tourist destination, and it has been estimated that the increase in visitor spending associated with the wetland could be $4 million to $11 million (Fine, 2003). It was also estimated that the overall value of the project could be twice these values.

*Herrerra Study of Stormwater Regulations Costs*

As a part of the effort to determine the costs of complying with stormwater regulations in Western Washington, Herrerra Environmental Consultants (2001) prepared designs for typical projects needed to contain and treat stormwater on site in small projects of new construction. In both cases, the systems were planned for a 1.7-inch rainfall. The first hypothetical project was a ten-acre residential development with 40 individual home sites. It was presumed that runoff from the homes would be collected in a detention pond. Construction of the permanent facilities was determined to cost $240,000 to $230,000, depending on the quality of soils. This is about $15 million per square mile.

The second hypothetical site was a restaurant built on a one-acre site, with the area not occupied by the building used as a parking lot. Runoff was to be collected in subsurface infiltration vaults. Costs were determined to be $280,000 or $570,000, depending on the permeability of the soil, or $175 million to $356 million.

*Dover Mall, Delaware*

The Dover Mall has 30 acres of parking lot or otherwise impermeable surface. Runoff drains to a wetland that is sized to retain a 1-inch rainfall (NRDC, 1999). It includes a forebay that allows containment of exceptional spills. The total project cost was $171,000 (although much of this was defrayed by in-kind donations). The wetland is considered a considerable esthetic resource. The cost was $3.5 million per square mile.

*Oakland Park Industrial Area, Florida*

A BMP treatment system was developed for five acres of Oakland Park that included auto repair shops, paint shops and plating facilities. A short treatment train was developed, including a trash removal basin and absorbent media. The system cost $261,000, and was successful in removing 71% to 95% of oil and grease, along with all trash and most sediment. Costs were $33 million per square mile of drainage.

*Clear Lake Packed Bed Wetland Filter System*

Clear Lake, in Orlando, Florida, receives runoff water from 121 acres of nearby urban land and water quality in the lake has deteriorated significantly as a result of pollution. Packed beds, consisting of 10 filter beds composed of crushed concrete or granite media with growing aquatic plants, allow removal of sediments and nutrients. An initial wet detention pond is used to contain the first flush. The system cost $917,646. In calculations, the system was considered a single installation treating 121 acres of drainage. Costs were $4.6 million per square mile.

*Sand Filters in Alexandria, Virginia*

Two sand filters were built to treat runoff from an airport parking lot near National Airport in Alexandria, Virginia. The area drained was 1.95 acres, and the filters cost $40,000. While some initial problems with anaerobic conditions were encountered, the filters eventually achieved good treatment. The cost, calculated from the data reported by FHWA (2003), was $12.9 million per square mile.

*Compost Filter Facility, Hillsboro, Oregon*

A compost filter was constructed to decontaminate water upstream of a grassy swale. The treatment train received water from a five-lane highway, draining a total area of 74 acres. The 1200-square-foot filter contained 120 cubic yards of compost and was constructed and filled for $13,700. The cost, not including the swale, was thus $110,000 per square mile of drainage area.

*Infiltration Trenches*

The Federal Highway Administration (FHWA 2003) has estimated the costs for constructing infiltration trenches as $C_A = 1317 \times V^{(0.63)}$ where C is the cost in dollars and V is the volume in cubic meters. Calculations for this report are made assuming the need to provide detention for a ¾-inch storm. For one square mile ($2.6 \times 10^6$ m$^2$), a ¾-in rainstorm will produce $5 \times 10^4$ m$^3$ of water. The cost per square mile is equal to the cost for each trench divided by the drainage area it serves, or $C_{mi2} = C_A/A = (1/A) \times 1317 \times V^{(0.63)} = 1.2 \times 10^6 \times A^{(-0.37)}$. The total cost for these systems thus declines as each system becomes larger—there are economies of scale. Costs for land are not included, but it is likely that trenches could be installed in land also used for other purposes. In some cases it might be necessary to collect more than ¾ inch of rain. On the other hand, the calculation assumes that no infiltration occurs in the trench during the storm. Also, this presumes that the runoff coefficient for the area served is 1.0—thus the typical systems described could treat a ¾-inch storm on totally impervious area or a 1.5-inch storm on an area with a runoff coefficient of 0.5, which is a commonly observed value. Thus the total seems a reasonable approximation.

*Infiltration Basins*

The Federal Highway Administration (FHWA 2003) has estimated costs for construction of open infiltration basins (dry basins) as $C = (V/0.02832)^{(0.69)}$, where C is the cost in dollars and V is the volume in cubic meters. As for the infiltration trenches, it is assumed the basins will be designed to treat a ¾-inch storm in an impervious drainage. Thus the cost per square mile is $C_{mi2} = C_A/A = (1/A) \times (V/0.02832)^{(0.69)} = 204{,}000 \times A^{(-0.31)}$. Costs for land are not included, and would be substantial. However, the basins could be used for other purposes for much of the year. Again, the systems assumed could treat a 1.5-inch storm in a drainage area with a runoff coefficient of 0.5.

*Bioretention Areas*

Stormwater can be collected in areas filled with highly permeable soils and planted with trees and other vegetation. Water that infiltrates is filtered by contact with the soils and may continue to move downward to replenish the groundwater. Much of it will also be taken up by the vegetation and returned to the atmosphere through evapotranspiration. The FHWA (2003) cost estimate for these bioretention areas is $10,000 per impervious acre, or $6.2 million per square mile of impervious watershed. Bioretention areas can readily serve multiple purposes as wildlife habitat and parks.

*Detention and Retention Wetlands*

The Federal Highway Commission Report (FHWA, 2003) has provided a general formula describing the cost of detention ponds as a function of size. Costs were estimated as $C_A = 168 \times V^{(0.699)}$, where $C_A$ is the cost in dollars and V is the volume of the pond in cubic meters. The cost per square mile is $C_{mi2} = C_A/A = (1/A) \times 168 \times V^{(0.699)} =$

$324{,}000 \times A^{(-0.301)}$. Land costs are not included, but these areas can serve other purposes during the larger part of the year when the weather is dry—they can be parks, wildlife areas, and playing fields.

*Detention Vaults*

In highly urbanized areas, water can be detained in underground vaults, which may be made of concrete or of corrugated steel pipe. Such systems primarily store water to avoid flooding or excessive hydraulic load on downstream systems, but some sedimentation may occur. This provides marginal treatment, but also requires that the vaults be cleaned out on a regular basis. The FHWA estimate for costs of such systems is $C = 38.1\times(V/0.02832)^{(0.6816)}$. Cost per square mile of drainage area is $C_{mi2} = (1/A) \times 38.1 \times (V/0.02832)^{(0.6816)} = 690{,}000 \times A^{(-0.3184)}$.

*Underground Sand Filters*

Sand filters are quite effective at removing particulates from urban stormwater, and are commonly employed upstream of other systems in order to protect them from excessive sedimentation. They can be installed underground in densely urban areas, but are correspondingly expensive. The FHWA estimate for such systems is $10,000 to $14,000 per impervious acre served, or $8.7 million per square mile. Here we have chosen the upper estimate because costs are likely to be high in the Los Angeles area.

*Surface Sand Filters*

Sand filters may also be constructed at the surface, which reduces their cost. However, they occupy a relative large amount of land area, and cannot contribute to a secondary use. There are strong economies of scale. For facilities serving more than 5 impervious acres, the FHWA estimate of cost is $3,400 per acre or $2.1 million per square mile.

*Dry Swales and Filter Strips*

A vegetated dry swale is an area of land shaped so that stormwater flows through it in a broad, relative flat stream. Flow through the grass removes sediments from the water. At the same time, significant amounts of infiltration may occur. It may be necessary to prepare the soils to maximize infiltration before the grass is planted. Swales can be used for other purposes during the periods when it is not raining. The FHWA estimate of construction costs for swales is $1500 per impervious acre, or $930,000 per square mile.

Filter strips are similar installations, in which the water flows as a flat sheet. The FHWA estimate of constructions costs for filter strips is $2000 per acre or $1,240,000 per square mile.

*Results from the ASCE-EPA BMP Database*

A cooperative effort of the American Society of Civil Engineers and the U.S. Environmental Protection Agency has compiled data on the success of best management practices. Data were carefully vetted, put as much as possible in common format, and arranged so that they could be searched according to several parameters. Several searches of the database were done to gather data for this study.

A search for dry detention basins, serving watersheds of 0-100,000 acres, with 0-30 in annual rainfall, produced 17 responses, of which only four included cost data. All of the four were associated with freeways and served small watersheds of 1-14 acres. This may be the reason why costs were exceptionally high.

A search for wetlands, serving watersheds of 0-100,000 acres, with 0-30 in annual rainfall, produced 10 responses, only one of which included cost data. Costs for this facility were exceptionally low. It was described as a "natural" wetland, perhaps implying that much of the system was already in place before construction was done.

A search for wetlands, draining 0-100,000 acres, with 0-30 in annual rainfall, produced 9 responses, including 6 with cost data. These also served very small watersheds, and costs per square mile were very high.

A search for hydrodynamic devices serving 0-100,000 acres, in areas of 0-30 in annual rainfall, produced 12 responses, including 8 with cost data. Costs ranged from $344,000 per square mile to $86 million per square mile, showing very strong economies of scale.

A search for grassy swales serving 0-100,000 acres, in areas of 0-30 in rainfall, produced 26 responses, including 7 with cost data. The cost per square mile ranged from $12 million to $341 million, and showed strong economies of scale. This was a surprising result—grassy swales are very simple and cheaply constructed systems—but it reflects the fact that each installation serves only very small areas.

## ESTIMATES OF COSTS AND RECOMMENDED APPROACH

Ultimately, stormwater pollution is a symptom of two anthropogenic changes: we are releasing pollutants into our local environment, and we have disrupted the hydrologic cycle of the Los Angeles Region by covering the soil with impervious surfaces. These changes have other symptoms as well. Local pollution impairs health, damages the esthetic quality of life, and reduces property values. Reducing infiltration increases runoff rates and the risk of flooding, and at the same time, reduces recharge of groundwater resources. Finally, impervious surfaces cannot support vegetation, and we suffer the loss of natural habitat, recreational areas, and aesthetic value of green space.

### Cost Estimates

The solution proposed in the report by Gordon et al. (2002)—advanced treatment plants to clean up stormwater after it has entered the storm drains—constitutes treatment of a single symptom without correction of the fundamental problem. It is expensive, and has little benefit beyond the single objective of protecting receiving waters. A more fundamental approach—eliminating pollutant releases and restoring the hydrologic cycle—is cheaper. Further, because it will mitigate all of the effects of pollution and hydrologic disruption, it will have benefits whose value exceeds the costs.

While a rudimentary cost-benefit analysis is attempted here, the limitations of such an approach should be kept in mind. Many costs and benefits are difficult to evaluate—the psychological benefit to citizens who live on a clean street rather than a trashy one, for example, or the long term effects on local business of a general perception of regulatory burdens. In past cost-benefit analyses, it has been common that costs and benefits that are difficult to measure have been assumed to be zero, certainly producing misleading results. It remains true that two good-faith investigators can produce quite different cost-benefit results, especially for a complex problem like stormwater quality control. Assumptions may depend greatly on the value system of the investigators. A recent cost-benefit study was criticized, for example, because it put a lower value on the lives of elderly persons. This is reasonable in the sense that the death of and older person represents fewer years of life lost, and less loss of earnings, and it is a common presumption in cost-benefit studies. However, there was outrage among those who felt that this approach was offensive to the elderly and the general principle that we all have equal rights.

In this particular study, because the costs and expenditures are of many different kinds, it was necessary to use a variety of estimation methods. The results are necessarily approximate, and comparisons among them must be viewed with caution. To use technical terms, contingent valuation studies are included with benefits transfer estimates, and results from various investigators are combined. We anticipate that these steps may be criticized, but we hope that we can provide a framework approach that can be improved and refined as further research is done.

Finally, cost-benefit analysis frequently ignores the issues that arise because the costs and benefits are not borne by the same parties. One might suggest that pollution should not be cleaned up if the cost of doing so exceeds the benefits of relief from the pollution. But it is commonly the case that the polluter who is saving money is not the same person who is suffering from the effects of the pollution. Does your neighbor have the right to throw his trash in your yard if he can show that it saves him more money than it costs you? The principle of "polluter pays" has a satisfying moral aspect and it also puts the incentives right—the parties with the ability to reduce pollution are given the motivation to find a way to do so.

For these reasons, and because in this short study the numbers are particularly only estimates, we present our cost benefit analysis with the caution that more precise and detailed assessments are desperately needed.

Cost estimates have been prepared by examining case studies. Reports were chosen where information was available for both the total cost of the system described and the land area served, or the initial stormwater retention volume, in order to calculate the cost of stormwater management per square mile of watershed. Several assumptions and caveats must be observed:

1. In the cost-per-square-mile calculations, no attempt was made to adjust costs on the basis of the amount of rainfall in the watershed. Sufficient data were generally not available for this purpose. In most cases, data came from areas where annual rainfalls are greater than in Los Angeles, and this may cause the cost estimates to be high.
2. In the cost-per-square mile calculation, the cost data were not available in a uniform format. It was not possible to calculate an accurate "present worth" including operations and maintenance costs for each case. In some cases operations and maintenance data were included, while in others they were not. In most cases operations and maintenance costs are low in comparison to installation costs, and they would be further reduced by discounting to present worth. Never the less, this may cause the cost estimates to be low.
3. Installation costs may vary depending on the slope of the land, the nature of the soils, depth to water table, local labor costs, and a wide variety of other factors that change with locality. No attempt was made to adjust the costs for these factors, and this may make the estimates high or low.
4. It is presumed that the systems described will be sufficient, in conjunction with source control efforts, to comply with water quality regulations. There was no case reported in which the quality control efforts were described as failing, or for which regulators asked for additional measures after the systems were complete. However, few data were shown for after-construction water quality, and most of the systems have not been in place for enough time to allow long-term assessment. The degree of success for source control efforts, while likely to be substantial, cannot be guaranteed.
5. Several of the projects described have been designed, but not implemented. It is assumed that they will perform as designed. In the case of the Federal Highway Administration formulas, these are regression results rather than individual case results.
6. It is likely that implementation in the Los Angeles area would involve projects that are larger than most of those listed. There likely will be economies of scale. This may cause the cost estimates to be high.

**Summary of Case Study Project Costs**
"I or D" refer to Implemented or Designed

| Project | I or D | Description | Unit Size, square miles | Cost, $M | Cost, $M per square mile |
|---|---|---|---|---|---|
| **Infiltration Systems** | | | | | |
| Fresno Metropolitan Flood Control District Regional Infiltration Basins (NRDC, 1999; Dave Pomaville, 2003) | I | 130 turfed or unturfed infiltration basins serving residential areas. Treats or infiltrates 98% of runoff over area of 120 square miles | 1 | | 2.5 to 3.7 |
| Study of Stormwater Regulations Cost (Herrerra Environmental Consultants, 2001) | D | Hypothetical calculation of costs for new residential development | 0.016 | .24 | 15 |
| Study of Stormwater Regulations Cost (Herrerra Environmental Consultants, 2001) | D | Hypothetical calculation of costs for new commercial development | 0.0016 | 0.28 to 0.57 | 175 to 356 |
| **Wetlands** | | | | | |
| Tule Pond, Alameda (Wetzig, 1999) | I | Stormwater treatment pond for urban runoff | 0.8 | 0.36 | 0.45 |
| Treasure Island, San Francisco Bay (NRDC, 1999: Galvanis, 2003) | D | Wetland treatment system for local runoff | 0.65 | 0.8 to 1.1 | 1.2 to 1.7 |
| Long Lake Retrofit, Littleton, Mass. (Roy et al., 2003) | I | Swales, constructed wetlands, bioretention cells, outreach | 1.5 | 0.63 | 0.42 |
| San Diego Creek Natural Treatment System Master Plan (Strecker et al., 2003) | D | Network of open-water ponds and wetlands in Newport Bay drainage, 120 square mile area | 2.7 | <60 | <0.5 |
| Murray City, Utah (NRDC 1999: Hill, | I | Golf course and wetlands treat runoff from 4.5 miles of I-215 | 9.5 | 1.0 | 0.11 |

| | | | | | |
|---|---|---|---|---|---|
| 2003) | | and the city | | | |
| Dover Mall, Delaware, (NRDC 1999) | I | Wetland installed on mall grounds drains 30 acres of 100% impervious cover | 0.048 | 0.17 | 3.5 |
| Sun Valley Project, Los Angeles County | D | Combination of various measures for flood and quality control in L.A. Basin | 4.4 | 172 to 297 | 39 to 68 |
| **BMP Treatment Processes** | | | | | |
| Oakland Park, Fla, industrial area (NRDC 1999) | I | Oil, grease, sediment, and trash removal by sedimentation and absorbance | 0.008 | 0.261 | 33 |
| Clear Lake Packed Bed Wetland Filter System (NRDC 1999: FHWA, 2003) | I | Oil, grease, nutrients, trace metal removal for water entering Clear lake | 0.2 | 0.92 | 4.6 |
| Compost Filter Facility, Hillsboro, Or. (FHWA, 2003) | I | Oil, grease, removal and filtration for highway runoff | 0.12 | 0.12 | 0.11 |
| Alexandria, Va, airport parking lot | I | Sand filters installed along the borders of a 1.95-acre parking lot | 0.003 | 0.04 | 12.9 |
| Bioretention Areas, FHWA cost estimate | D | Areas of highly permeable soil planted with trees and other vegetation | | | 6.2 |
| Underground Sand Filters | D | Porous medium filters placed in underground vaults, appropriate for highly urban areas | | | 8.7 |
| Dry Swales | D | Broad, shallow vegetated drainways covered with vegetation, usually grass | | | 0.93 |
| Surface Sand Filters | D | Porous medium filters installed at the surface | | | 2.1 |
| Filter Strips | D | Flat vegetated drainways covered with vegetation, usually grass | | | 1.2 |
| Port of Seattle container area cleanup | I | High quality street sweeping with sediment trap catch basins | | | 3.1 |
| **Cost:Area Formulas from FHWA** | | | | | |
| Infiltration trenches, FHWA cost estimate | D | Gravel-filled trenches. Infiltration eliminates runoff discharge. | $C_{mi2} = C_A/A$<br>$= (1/A)\times 1317\times V^{(0.63)}$<br>$= 1.2\times 10^6\times A^{(-0.37)}$ | | |

| | | | | | |
|---|---|---|---|---|---|
| Infiltration basins, FHWA cost estimate | D | Open basins, dry at most times, store and infiltrate runoff. Infiltration eliminates runoff discharge. | $C_{mi2} = C_A/A$<br>$= (1/A)\times(V/0.02832)^{(0.69)}$<br>$= 204{,}000\times A^{(-0.31)}$ | | |
| Detention and retention wetlands, FHWA cost estimate | D | Wetlands used for treating stormwater, with storage capacity available | $C_{mi2} = C_A/A$<br>$= (1/A)\times168\times V^{(0.699)}$<br>$= 324{,}000\times A^{(-0.301)}$ | | |
| Detention vaults, FHWA cost estimate | D | Underground reservoirs for storage of runoff to reduce peak flows | $C_{mi2} =$<br>$(1/A)$<br>$\times38.1\times(V/0.02832)^{(0.6816)}$<br>$= 690{,}000\times A^{(-0.3184)}$ | | |
| **Results from ASCE-EPA BMP Database** | | | | | |
| *Dry Detention Basins* | | | | | |
| I-605/SR-91 EDB | I | | 0.0013 | 0.077 | 60 |
| I-5/Manchester (East) | I | | 0.0077 | 0.33 | 43 |
| I-5 SR 6 | I | | 0.0085 | 0.14 | 17 |
| I-75/SR-78 EDB | I | | 0.022 | 0.82 | 38 |
| *Wetlands* | | | | | |
| Swift Run Wetland | I | | 1.95 | 0.049 | 0.025 |
| *Sand Filters* | | | | | |
| I-5/SR-78 P&R | I | | 0.0013 | 0.22 | 170 |
| Escondido MS | I | | 0.0013 | 0.45 | 348 |
| Eastern Eastern Regional MS | I | | 0.0024 | 0.34 | 141 |
| Foothill MS (Sand Filter) | I | | 0.0029 | 0.48 | 164 |
| Termination P&R | I | | 0.0045 | 0.46 | 102 |
| LaCosta P&R | I | | 0.0045 | 0.23 | 49 |
| *Hydrodynamic Devices* | | | | | |
| Jensen Precast (UVA)-Phase II | I | | 0.00045 | 0.039 | 86 |
| I-210/Orcas Avenue | I | | 0.0018 | 0.04 | 22 |
| Jensen Precast, (Sacramento) | I | | 0.0032 | 0.062 | 19 |
| I-210/Filmore Street | I | | 0.0040 | 0.05 | 12 |
| Charlottesville Stormceptor | I | | 0.0040 | 0.017 | 4.2 |
| Sunset Park Baffle Box | I | | 0.040 | 0.023 | 0.57 |
| Indian River Lagoon CDS Unit | I | | 0.098 | 0.055 | 0.56 |
| Austin Rec Center | I | | 0.15 | 0.05 | 0.34 |

| | | | | | |
|---|---|---|---|---|---|
| OSTC | | | | | |
| *Grassy Swales* | | | | | |
| I-650/SR-91 Swale | I | | 0.00032 | 0.11 | 341 |
| Cerrito MS | I | | 0.00065 | 0.06 | 93 |
| 1-605/DelAmo | I | | 0.0011 | 0.13 | 115 |
| I5/I-605 Swale | I | | 0.0011 | 0.073 | 64 |
| Monticello High School | I | | 0.0013 | 0.015 | 11 |
| SR-78 Melrose Dr | I | | 0.0039 | 0.13 | 34 |
| I-5 North of Palomar Airport Road | I | | 0.0074 | 0.14 | 18 |
| I-650/SR-91 Swale | I | | 0.00032 | 0.11 | 341 |

**Economies of Scale**

The costs listed in Table 2 reflect the cost for an individual facility ("Cost, $M" and "Cost, $M/mi$^2$") and associate it with the drainage area served, referred to as the "Unit Size". The costs per square mile for the individual units can be plotted to determine the effects of unit size (Figures 1 and 2). While there is a great deal of scatter in the data, it is clear that there is considerable economy of scale. Units serving drainages of a half square mile are typically 30% more expensive that those serving 1 square mile. Those serving drainages of one-tenth square mile are twice as expensive and small installations are extremely expensive in dollars per square mile. The most notable example of this is grassy swales: while each unit is relatively inexpensive, their small service areas make them very expensive per square mile served.

For some of the BMPs there are not sufficient data to judge the economies of scale, and as described, all of the data must be taken as approximate. Never the less, it seems that there is a good case to suggest that regional systems for handling runoff water will be most economical. This is clearly true of wetlands and infiltration basins, which are likely to be the most widely used approaches in the Los Angeles Region as a whole. This supports the position that the best solution will be a wetland or an infiltration basin also serving as a park, playing filed, or wildlife habitat as the stormwater management unit for a neighborhood of a square mile or greater.

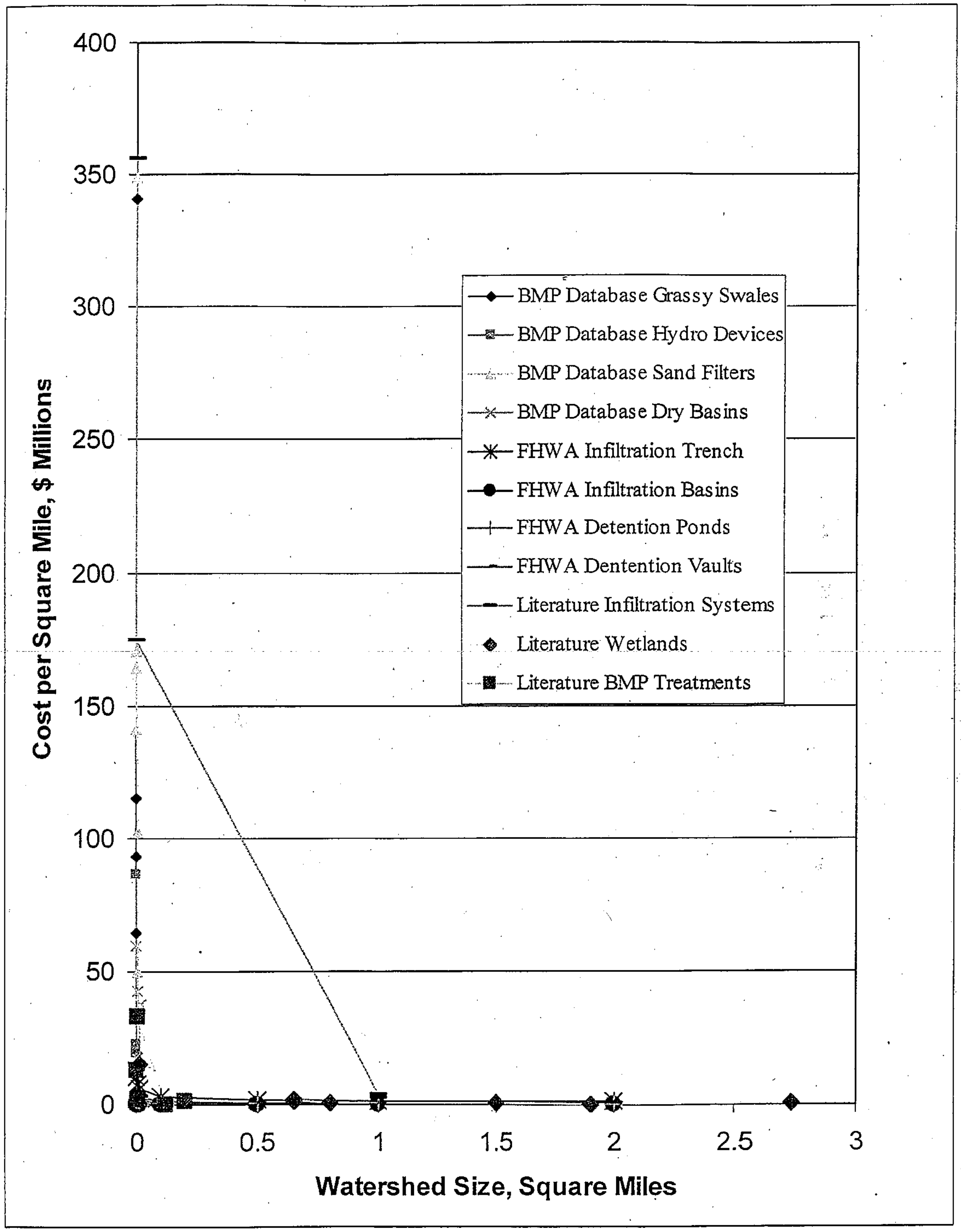


Figure 1. Plot of data for which costs per square mile and unit areas are known.

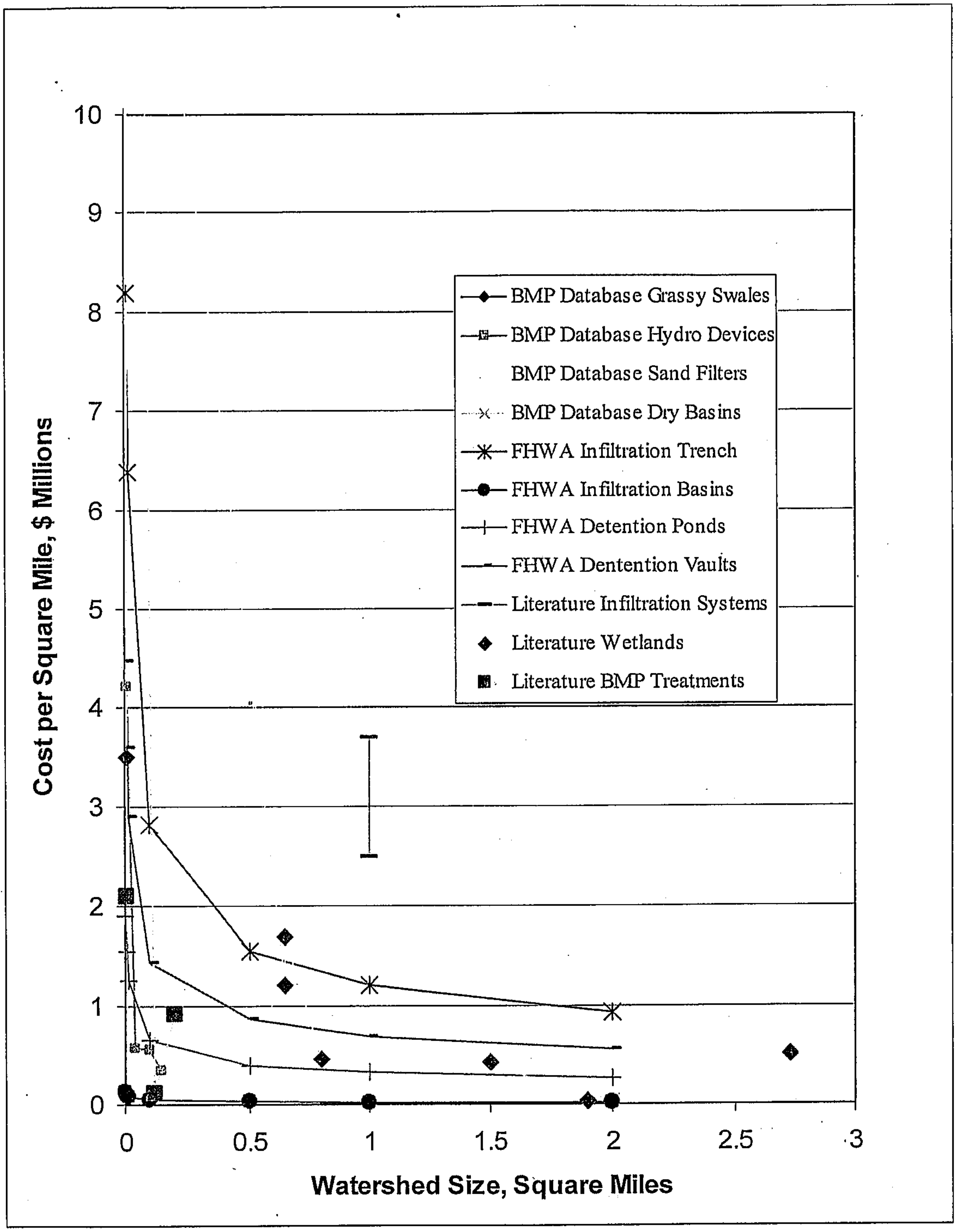


Figure 2. Cost per square mile versus unit size. Data are the same as those shown in Figure 1, but the axes have been magnified to show detail near the origin. Many data points fall outside of the plot.

**Overall Costs of Stormwater Quality Control**

It remains very difficult to produce an estimate of the total costs for complying with regulations in the Los Angeles Region. While there is substantial information on individual units that have been designed or implemented elsewhere, local factors are likely to make costs different in the Region. In most cases, it seems likely that costs in the Los Angeles Region will be higher than those reported elsewhere because land and labor costs are higher. Therefore, where a range of values is given, we have chosen the higher numbers.

This difficulty is compounded by the great variability in the data reported. To give just one example, the Federal Highway Administration formula estimates the cost of an infiltration basin needed to serve one square mile as $200,000. At the other extreme, the Herrerra Consultants report said that a detention/infiltration system for a residential area would cost $15 million per square mile. In preparing our total estimate, we have avoided using data that seem like outliers in comparison to the general run of the data.

The results compiled suggest two possible scenarios for stormwater quality control. The first approach is to rely on non-structural BMPs, such as programs to reduce littering, control pet waste, collect trash, prevent release of pollutants, and clean existing drains. This approach is less expensive because it involves no construction. However, there remains considerable doubt whether it will be sufficient to meet stormwater quality goals expressed as TMDLs (Total Maximum Daily Loads). Control of pollutant release will be only partial—we cannot expect that everyone will comply with the rules—and the amount of runoff will be reduced only slightly.

The second scenario presumes implementation of non-structural BMPs (except storm drain cleaning) and construction of a network of wetlands and infiltration basins sufficient to capture the first three-quarters of an inch of rainfall, which typically carries the bulk of the pollutants. These relatively simple installations are not likely to be sufficient without complementary measures to reduce releases of coliforms, trace metals, fertilizers and toxic organics. Wetlands help to remove these, but will not be effective if inputs are too high. Infiltration avoids all pollutant discharge, because it prevents release of the water, but it is necessary to protect groundwater quality, so once again, inputs must be restricted. The wetlands and infiltration basins would be designed to have sufficient retention capacity to hold the first ¾ inch of rainfall—this "first flush" carries most of the pollutants, but pollutant discharges must be sufficiently reduced so that subsequent flows can be discharged directly to storm drains.

In combination with the non-structural BMPs, wetlands and infiltration basins (designed as "stormwater parks") are likely to bring stormwater quality into compliance. This system will be more expensive, but it also carries greater secondary benefits: the region will gain much-needed greenspace, property values will be improved, and most important, it will substantially increase the availability of groundwater.

It is our recommendation that the responsible municipalities and agencies in the region begin at once on assessing stormwater quality on a neighborhood basis and implementing the non-structural controls. As the success of these measures is measured, it will become apparent whether the structural BMPs are needed. It seems certain that they will be needed in some areas, but they may not be needed throughout the region. Thus our estimate of costs ranges from a minimum budget needed for the non-structural

BMPs to a maximum representing the cost of an area-wide system of wetlands and infiltration basins. The following section provides the details of how the cost estimates were prepared.

*Non-structural BMPs*

An estimate of costs for non-structural BMPs has been prepared by the American Public Works Association (APWA, 1992). They defined five levels of BMPs that might be workable, with the appropriate level depending on the stringency of discharge requirements and the success of the individual measures. Their analysis included ten source control measures with cost data, and has been used as the starting point for the analysis here. Our treatment of each measure is described in the following paragraphs.

No littering ordinance. Litter laws are in place in the region, but there is a need for far more vigorous public education and enforcement. The APWA study determined that each municipality would spend $20,000 to put an enforcement program in place, and hire a half time person to manage the program ($30,000 per year). There are about a hundred municipalities in the Los Angeles Region, so this implies a startup cost of $200,000 and yearly costs of $3 million. Some officers will be necessary, but it is assumed that their pay will be covered by revenue from fines. Total costs are estimated to be $3 million plus the present worth of $3 million per year at 3%, or $103 million.

Pet waste ordinance. APWA predicted that the effort to control pet waste would be similar to that for litter, and estimated the same costs.

Chemical use and storage ordinance. APWA determined that a program to control the use and storage of chemicals would be similar is scope and cost to that for litter or pet waste. The same costs are estimated here. This would include the cost of programs to bring auto dismantlers and other local businesses into compliance.

Recycling programs. APWA predicted less trash would be discarded if convenient recycling programs were in place. Because these currently exist in most Los Angeles Region cities, and are justified by other concerns, no additional costs are estimated for this purpose.

Public education programs. Developing public support for stormwater quality control and explaining the need for citizen action will be vital to its success. The APWA determined a program costing $275,000 in each municipality would be necessary. However, it would be confusing and unnecessarily duplicative to have each of the one hundred municipalities in the Los Angeles Region conduct its own program. We instead assume a single program will be funded at the level of $5 million per year, which is approximately the current rate of expenditure. It also seems likely that education will not be needed indefinitely—to the degree that the message is successful, it will certainly become ingrained after perhaps ten years of advertising. We therefore estimate a total of $50 million for public education.

Vacant lot cleanup programs. This function will be part of the improved trash collection program, so funds are not separately allocated.

Spill prevention ordinance. APWA determined a separate program would be necessary to reduce the frequency of chemical spills and facilitate their rapid cleanup. This function has largely been overtaken by hazardous waste management regulations, and so is estimated to require no additional costs here.

Program to prevent illicit discharges. APWA determined that vigorous efforts would be needed to find and eliminate illicit discharges to the storm drain system. We agree that this will be necessary to avoid loads of non-biodegradable pollutants, such as trace metals, on treatment wetlands and infiltration basins, and to prevent excessive loading of organic contaminants and coliforms. APWA predicted a cost of $4 per acre of watershed to start, and $50 per acre per year thereafter in order to deploy and monitor sampling devices and to trace down points of discharge. For the 2,050 square miles in which stormwater protection is needed, this amounts to $6.5 million in capital expenses and $80 million per year in ongoing costs. We expect however, that many illicit connections will be found at first, and that after these are eliminated, only a small program will be needed to detect new illicit connections. We therefore estimate that the ongoing costs will continue for only five years, totaling $407 million.

Improved cleaning of storm drains. During dry periods, storm drains collect trash from illicit dumping and wind blown litter (we expect no trash will enter through the catch basins because screens will be installed). Sediments also accumulate in the channels. Releases to the rivers and ocean could be reduced by a summer program of storm drain cleaning. The APWA estimates such a program can be put in place for $21 per acre per year, or about $27 million per year over the area of concern. The present worth of $27 million per year is $900 million (assuming an interest rate of 3%). No storm drain cleaning is expected for the wetlands and infiltration scenarios, on the presumption that trash and sediments will be removed from the water before it enters the drains.

Trash control. Trash must be removed from the runoff. A settlement agreement on Trash TMDL between the LA Regional Water Board and the City of Los Angeles includes spending of $168 million to reduce trash releases by 50% in five years. Cleaning up the region required removing all of the trash from an urban area more than twice the size of the city. Thus the estimate of $600 million seems reasonable.

Low flow treatment. One of the best steps, in terms of water quality benefits per dollar, is to use excess capacity in the wastewater treatment plants for treatment of low flows. This will keep the rivers and oceans clean for most of the year at little additional cost. The City of Los Angeles estimates the cost of building the necessary diversion structures at $14 million (Kharaghani, 2003). The urban region is about twice the size of the city, so we have estimated a total cost of $28 million. This does not include operation costs. While there will be modest cost increases associated with the greater flows, the biggest costs are associated with the installed treatment capacity, which is already in place.

Improved street sweeping. The APWA report determined that sweeping should be improved by increasing its frequency. Research results developed since the APWA report suggest that more frequent sweeping with traditional brush machines produces only a modest improvement. However, changing to vacuum sweepers is effective, and can remove up to 50% of particulate pollutants.

The upgrade of street sweeping in the region will require purchasing new vacuum-type sweepers to replace those currently in use. There are about 400 street sweeping machines in use, which must be replaced once every four years, so 100 machines will be purchased each year. Vacuum machines cost about $150,000 rather than the $75,000 for standard machines. Thus the additional costs of higher quality sweeping are $75,000 per machine or about $7.5 million per year. Assuming an interest rate of 3%, this has a present worth of about $250 million.

Costs for on-site BMPs for private firms. It is anticipated that application of non-structural BMPS will include requirements that businesses make efforts to reduce pollution and runoff from their facilities. Efforts are likely to be highly variable: an accounting firm whose work is all done in offices might need to do no more that redirect its roof runoff to landscaping areas. A manufacturing facility might install sand filters and oil-water separators. Parking lots may be remodeled. It is difficult to provide an estimate for these efforts, but a general approximation for the total can be approached if firms are considered by size (Table 3). Data on the number of firms within chosen size ranges, measured by the number of employees, have been compiled for Los Angeles County by the California Employment Development Department (2001). Again, this area is not the same as the Los Angeles Region governed by LA Regional Water Board, but there is substantial overlap and the demographics are similar.

**Table 3. Estimate of On-site BMP Costs for Los Angeles County Firms by Size Class**

| Number of Employees | Number of Firms | Average Cost per Firm | Total Costs |
|---|---|---|---|
| 0-4 | 219,974 | 10 | $2,199,740 |
| 5-9 | 37,125 | 500 | 18,562,500 |
| 10-19 | 25,366 | 1,000 | 25,366,000 |
| 20-49 | 19,682 | 2,000 | 39,364,000 |
| 50-99 | 7,745 | 5,000 | 38,725,000 |
| 100-249 | 4,239 | 10,000 | 42,390,000 |
| 250-499 | 1,138 | 25,000 | 28,450,000 |
| 500-999 | 408 | 50,000 | 20,400,000 |
| 1000+ | 260 | 100,000 | 26,000,000 |
| Totals | 315,937 | | 241,457,240 |
| | | Average cost per firm | $764 |

Most small firms will not spend any money, so the average cost per firm is expected to be very low. A few might be required to improve trash disposal methods or reroute their rooftop drainage. At the other extreme, the largest companies might improve trash disposal and materials handling methods, build infiltration system planters, install oil-water separators, institute parking lot and work area sweeping. Companies that install new parking lots or reconstruct old ones may incur significant costs.

Costs for compliance with the "3/4-inch rule". The SUSMP regulations promulgated by the LA Regional Water Board require that new developments larger than one acre and redevelopment must provide for infiltration or minimal treatment of runoff from the first ¾-inch of rainfall from a storm event. It is difficult to determine how much this will cost. Proponents have suggested the costs will be minimal, while opponents have predicted high costs. Experts contacted during this study were of the general opinion that landscaping designed to infiltrate the runoff from a ¾-inch storm would be different, but not significantly more expensive, than traditional landscaping. On the other hand, engineers in the discipline believe that most builders are choosing treatment systems rather than infiltration. The stormwater control costs will likely be a small fraction of building costs. Ultimately, we have concluded that there are not sufficient data to make a numerical cost estimate. The costs are therefore described here only as "modest", and further study is recommended.

*Wetlands and Infiltration Basins: Estimate Based on Cost per Square Mile of Watershed*

The land within the Los Angeles Region varies from lightly settled areas, like the upper reaches of the Santa Clara River Watershed or the Santa Monica Mountains, through neighborhoods of single family homes with yards, to the extremely dense development of downtown Los Angeles or the Wilshire District. There are about 1,375 square miles of incorporated cities in Los Angeles County. The region of the LA Regional Water Board includes parts of Ventura County, and parts of both counties that are not incorporated are never the less populated. To evaluate the possible alternatives for runoff control, we have conceptually divided the 3,100-square-mile region that is under the jurisdiction of the Los Angeles Regional Water Quality Control Board into four parts 1000 square miles is estimated to be of "low density", requiring some runoff BMP treatment, but having sufficient land for development of treatment wetlands or infiltration systems. 1,000 square miles is estimated to be "high density" requiring infiltration systems but excluding wetlands. 50 square miles is estimated to be extremely dense downtown development, requiring some more sophisticated BMP treatment systems. The remainder of the region is considered rural, and we presume the only cost is for source control outreach and enforcement. These definitions and numbers are approximate, but there is also flexibility in the applicability of the various technologies.

For the low density urban areas, we assume some combination of infiltration systems and treatment wetlands will be constructed. The range of reported costs for treatment wetlands runs from $110,000 per square mile for Murray City, Utah, to $1.7 million per square mile for the Treasure Island wetland in San Francisco. The San Diego Creek wetland system seems an excellent example—it is designed for a populated region of Orange County that is quite similar to many areas in Los Angeles County. However, it is specifically designed to treat low flows only, and the total cost of the system has not been provided (except that it is less than $500,000 per square mile). The Long Lake retrofit also seems like an appropriate example. It uses a mix of wetland, infiltration and biological BMPs in an urban residential area, and has a well-established cost of $420,000 per square mile. We have therefore used this value in our total estimate of $420 million for the low density areas.

In areas of high density housing, where yards are small, or in industrial areas with large roof and parking areas, runoff coefficients are higher and there is less land available. Here it seems likely that infiltration systems will be necessary. The best example for comparison is the Fresno Metropolitan Flood Control District, which installed 130 basins over an area of 120 square miles, with many of the facilities dedicated to multiple uses as parks and playing fields. Cost estimates for the system range from $2.5 million to $3.7 million per square mile. While a similar system built in the Los Angeles Region could take advantage of existing parks, power line rights-of-way, parking lots, and other available land, it seems appropriate to use the higher number because land here will be more expensive. Thus we estimate cost in these areas to be \$3.7 million per square mile for a total of \$3.7 billion.

In extremely dense areas, neither wetlands nor infiltration systems will be possible. Pollutant loads, despite source control efforts, will be considerable in the near future. Underground sand filters, sediment traps, oil and grease adsorbants and other more elaborate treatment BMPs will be needed. The lowest-cost processes are filter strips, dry swales and bioretention areas, but these require space that is unlikely to be available (the Hillsboro, Oregon compost filter, at \$110,000 per square mile is considered an outlier). Even the Alexandria, Virginia airport parking lot solution is unlikely to be workable because so much of the parking area is in multi-level structures in downtown areas. This combination of more pollutants and less space suggests that the Oakland Park, Florida system for treating industrial runoff is the best case example. Its cost was equivalent to \$33 million per square mile, for a total of \$1.65 billion over the extremely dense urban area.

Together, this approach estimates that the total BMP facilities cost will be about \$5.7 billion.

*Wetlands and Infiltration Basins: Estimate Based on Needed Retention Capacity*

Investigators working on the Sun Valley Project (Los Angeles County Department of Public Works, 2003, Figure 4-3 of page 4-8) have designed several BMPs and provided carefully calculated cost estimates. These are recent figures, reduced to present worth, and reflecting the local conditions in the urban Los Angeles Region. They provide costs in terms of dollars per acre-foot of stormwater storage capacity for several BMPs. Three examples have been chosen for consideration here: Stonehurst Park and Wentworth Park (which simply lower the park level to two feet below the surrounding area so that they serve as infiltration basins, or "stormwater parks"), and storage in below-street infiltration vaults. A system that stores the runoff from a ¾-inch storm will comply with SUSMP requirements. In the low density areas, it is estimated that the runoff coefficient is 0.4. In the high density areas, it is estimated to be 0.6, and in the extremely dense areas it is estimated to be 1.0.

We estimate that the low-density areas can be served at the Stonehurst Park price, the high density areas can be served at the Wentworth Park price, and the extremely dense areas can be served by street infiltration vaults. This approach to estimating the total cost is completely independent of the first approach, but the final estimate of \$4.0 billion for BMP facilities is reasonably similar.

*Wetlands and Infiltration Basins: Estimation of Total Costs from the APWA Study*

The APWA study produced total estimates for costs for the nation for five scenarios for stormwater quality control. One estimate was for a system of detention basins and wetlands, as is being proposed for the structural BMPs described here. They estimated that a national system would cost \$91 billion. For 260 million people in the United States, this is about \$350 per capita. For the 10 million people in the Los Angeles Region, this produces an estimate of \$3.5 billion. The APWA anticipated maintenance costs for detention and retention basins at about 1% of the construction cost per year. Discounted to present worth, this increases the total cost by 33%, or \$1.2 billion. APWA numbers thus indicate a total cost of $4.7 billion. This estimate is similar to those shown for the entries in Table 3 for facilities costs for alternatives B and C.

*Wetlands and Infiltration Basins: An "Upper Bound" Provided by the Sun Valley Study*

The Sun Valley study developed a detailed design for a 4.4 square mile watershed that currently has no storm drains. It was designed to contain the water from a 50-year, 3-day storm—14.8 inches of rain—using stormwater parks and below-street infiltration vaults. Because this approach will infiltrate essentially all of the rain that runs off from the area, and because the design criterion of 14.8 inches greatly exceeds the ¾ inch assumed here, it unquestionably constitutes a plan that would overcomply with the strictest imaginable stormwater quality control regulations. Further, because it is a complete and detailed design, it is essentially certain that it can be built for the cost estimated. Figures are recent, and reflect the costs of construction in the Southern California area.

The costs determined can therefore serve as an "upper bound" multiple benefit expenditure that a municipality could imaginable be required to incur—while there is every reason to suppose that the easier goal of stormwater quality control can be done for a much lower cost. The low cost alternative described was $171 million for 4.4 square miles, or $39 million per square mile. For the 1050 square miles of the high density and extremely dense urban Los Angeles Region, this would result in a cost of $41 billion. Wetlands for the low-density areas and trash control for the entire region would add about $1 billion more. Thus we can say with great certainty that no alternative more expensive than $42 billion will be needed.

**Overall Benefits of Stormwater Quality Control**

*The Esthetic Value of a Clean Ocean*

Much of the value of living near clean streams and a pollution-free ocean is difficult to quantify. People enjoy the view, they like watching wildlife, and they prefer vegetation and sand and water to pavement. Some efforts to place a dollar value on these benefits have been made by the EPA (1999) and others (Kramer, 2003; Soderqvist, 2000; Whitehead, et al., 2000).

Soderqvist asked residents in the area of the Stockholm archipelago how much they were willing to pay in order to reduce eutrophication of the nearby ocean. The effects of oceanic eutrophication are relatively subtle—less obvious than floating trash or debris washed up on the beach. He determined the willingness to pay to be between $54 and $90 per person.

Whitehead investigated resident willingness to pay for reduction of eutrophication of the Neuse River Basin in North Carolina. He found 44,000 landowners were willing to pay about $76 each for the water quality improvement.

Kramer surveyed people in the area of the Catawba River in North and South Carolina, asking about willingness to pay for improved water. The average result was $139 per taxpayer.

The EPA surveyed people across the U.S., asking about their willingness to pay for the various services associated with improvements in fresh water quality. They found people willing to pay $210 per household for improvement of water quality sufficient to support boating, $158 for the further improvement sufficient to support fishing, $177 for further improvement sufficient to allow swimming, and $158 for improvement sufficient to support natural aquatic life. Of the total of $703, however, only 67% was ascribed to local water quality improvement, while the rest was associated with improvement nationwide. Assuming 2.5 persons per household, this results in an estimate of $188 per person for willingness to pay for local freshwater improvements, similar to the estimate by Kramer for the Catawba River.

We have chosen the EPA estimate for freshwater improvements: the higher estimate seems reasonable because freshwater resources in the LA basin are generally in very poor condition, and because we have ignored the national effect (their results indicated that people throughout the nation were willing to pay for improvements throughout the nation—we are not counting the willingness of people outside the LA Region to pay for improvements here, and that number is not zero). Adding this to a mid-range value of the Soderqvist estimate for improvements in ocean water quality produces a result of $260 per person. This seems a quite reasonable value. 9.5 million people live in the Los Angeles Region, so this value indicates a total willingness to pay, based solely on the value of living in a region of clean waters, of about $2.5 billion.

Larsen and Kew (2003) have surveyed residents of California to determine their total willingness to pay for removing all impairments from bodies of water in the state. They determined that the average willingness to pay was $15.46 per month. Assuming 2.5 persons per household, this is $6.18 per person per month. For 9.5 million residents in the Los Angeles Region, this is $58.7 million per month, with a present worth of $23 billion. This represents the value of removing all impairments—including those caused by wastewater pollution, shoreside development, pollution from boats, and others. Our estimate for stormwater pollution alone is about one-tenth of this. Thus the Larsen and Kew results suggest our estimate is reasonable and conservative.

General support for these numbers was found in a survey done for the Packard Foundation performed by Mark Baldassare (Weisse, 2003). He determined that seven of ten Californians are concerned about the decline in coastal resources. Sixty-nine percent said the condition of the coastline is very important to their quality of life, and 75% visit the coast at least several times each year. Seventy-two percent favor reducing stormwater pollution, even if the cost leads to higher utility bills.

*Ecosystem Services*

A primary purpose of stormwater quality control is protection of nearshore marine ecosystems. These ecosystems provide humanity with a wide variety of services, ranging from educational opportunity to fish resources to chemical maintenance of the atmosphere. While the effort to value such ecosystem services is necessarily difficult and approximate, some studies have been made. Costanza, et al. (1997) in an article published in the respected journal *Nature*, assessed the value of coastal ecosystems at $12 trillion per year worldwide. The World Resources Institute estimates that there are 1.6 million kilometers of coastline (measured at a resolution of 1 kilometer). If we assume that stormwater discharges from the Los Angeles Region affect about 100 miles, or 160 kilometers of coastline, this is 0.01% of the world's total, suggesting that the value of local coastal resources is $1.2 billion per year. Assuming an interest rate of 3%, this income stream has a present worth of $40 billion. Finally, we can make the general approximation that stormwater pollution reduces the services provided by the local coastal ecosystem by 5%. This suggests that the value of lost services is $2 billion.

This number is quite approximate. It must secondly be interpreted thoughtfully because it includes services such as nutrient cycling and maintenance of the atmosphere, which are of undoubted value to the world, but which do not show up in the daily budgets of local citizens or local municipalities. The services are nevertheless quite real and quite valuable, and should be included in the accounting.

*Additional Water Supply*

Infiltration of stormwater will add to area groundwater reserves. These are a valuable resource that currently provides a substantial fraction of the Los Angeles Region water supply. Water that is infiltrated from the stormwater quality control system will add to local resources, reducing the need for imported water. We assumed that water will be collected from 2050 square miles. Rainfall ranges from 12 to 16 inches per year in the region, and infiltration is from 2 to 8 inches per year. It is conservative to assume that installation of a distributed system of infiltration basins will increase infiltration in this area by an average of 3 inches per year, corresponding to collection of four storms of ¾ inches (or a larger number of smaller storms). Thus total infiltration will be 300,000 acre-feet per year. Some of this may be unrecoverable, having entered contaminated or otherwise unusable aquifers. However, even this will contribute to reducing the problems of seawater intrusion. We estimate that about 90% or 270,000 acre-feet of the infiltrated water will be available.

Current importation costs are about $450 per acre-foot. However, current supply shortages are forcing serious consideration of desalination as an alternative source because political and environmental factors preclude significant increases in importation. We predict that continued growth in the Los Angeles Region will require that water be obtained from such high-cost sources, so we have used $800 per acre-foot as the value of the infiltrated ground water. Further, even if water is available for $450 per-acre foot, this is only the marginal financial cost of import—the true life cycle cost, including environmental impacts in source areas, is surely much higher. 270,000 acre-feet of water per year at $800 per acre-foot amounts to $216 million per year. The present worth of this income stream is $7.2 billion.

The appropriate number is highly dependent on assumptions: if conservation measures are effective and growth is slow, desalination might not be necessary. However if we include the costs of political friction with source areas, and the environmental impact of water transfers on those areas—that is, the full life-cycle cost of imported water, even the cost estimate of $800 per acre-foot may be low.

*Flood Control*

The flood control system in Los Angeles County is currently designed to cope with runoff from areas with a runoff coefficient on the order of 0.5. Stormwater quality control measures could substantially reduce this number—currently the coefficient for the San Gabriel Valley, measured below the spreading grounds at Whittier Narrows, is 0.05. Calculations suggest that the recent Army Corps of Engineers project that raised the embankments along the lower Los Angeles River have eliminated the 100-year flood plain for now, and property owners have correspondingly been relieved of flood insurance costs of $20 million or $30 million per year. However, if development continues to increase the runoff coefficient of the region, progressively more expensive projects will be required—it is likely that further protection would require rebuilding many bridges. Alternatively, flood insurance will once again be necessary, and uninsured properties will be at risk. It is perhaps reasonable to presume that infiltration systems will avoid the cost of the next embankment project, which could easily costs twice as much as the one just completed, or $400 million.

A second estimate can be developed this way: The National Flood Insurance Program says there are 25,620 policies held in Los Angeles County with an average premium of $550, for a total yearly cost of $14 million. The present worth at 3% is $466 million. Presumably, most but not all of this could be avoided with a complete stowmwater quality control system. Thus the estimate of $400 million seems reasonable.

*Property Value Improvements from Greenspace and Water*

Certainly additional parks and other greenspace would add to property values. Developers frequently add central lakes or greenspace to large developments, demonstrating their belief that the value of the land for additional housing is less than its value as an amenity. In a study compiled in 1995, the U.S. EPA said (U.S. EPA, 1995):

> "People have a strong emotional attachment to water, arising from its aesthetic qualities--tranquility, coolness, and beauty. As a result, most waterbodies within developments can be used as marketing tools to set the tone for entire projects (Tourbier and Westmacott, 1992). A recent study conducted by the National Association of Home Builders indicates that "whether a beach, pond, or stream, the proximity to water raises the value of a home by up to 28 percent." A 1991 American Housing Survey conducted by the Department of Housing and Urban Development and the Department of Commerce also concurs that "when all else is equal, the price of a home located within 300 feet from a body of water increases by up to 27.8 percent" (NAHB, 1993). Dick Dillingham, President of the National Association of Realtors' Residential Sales Council, declares, "Water makes a difference . . . there is such a very small supply of properties that can claim a water location and it is something you cannot add" (Lehman, 1994)."

Homes overlooking the new wetlands and greenspace will see the greatest increase in property values. Those farther away will appreciate less. A study reported by Fairfax County, Virginia, (Environmental Coordinating Committee, 2003) interpreted the EPA results and concluded that an aesthetically valuable pond raises the value of nearby houses by $10,000 each. In Los Angeles County, the median home is valued at about $400,000, so a $10,000 increase is about 2.5%, which seems a reasonable number. Demographic data for Los Angeles County (This is not the same as the Los Angeles Region governed by the Water Quality Control Board, but there is considerable overlap, and the demographics are quite similar) indicate there are 3.27 million homes, of which 47.9%, or 1.55 million, are owner-occupied. We expect that about one-third of these, or 500,000 homes, would benefit from additional greenspace in a complete stormwater control system (the others could be too remote, or might already have sufficient greenspace). Increasing the value of each home by $10,000 provides a total benefit of $5 billion.

*Improved Property Values from Trash Control*

Enforcement of litter laws and improved street cleaning would improve the appearance of our neighborhoods. It is believed that the esthetic improvement would have a value to individuals at least equal to the esthetic benefits of a cleaner ocean, so we have valued this at $100 per person, for a total of $950 million.

*Cost Savings from Reduced Dredging*

Costs for sediment dredging and disposal in area harbors range from about $10 per ton, when the sediment is clean and a nearby disposal site is available, to $30 per ton when the sediment is contaminated or the disposal site is distant. Disposal of sediments classified as toxic may cost $100 per ton. Personnel at Los Angeles Harbor estimate that about 40% of currently dredged sediment is contaminated, and occasional loads are toxic. In general, acceptable disposal sites are becoming harder to find, so distant sites are likely to be the rule. Thus, an estimate for future sediment removal of $30 per ton is reasonable. The Environmental Protection Agency has estimated overall costs and effectiveness for sediment control at construction sites, and the results indicate that preventing the runoff of a ton of sediment costs from $69 to $86 (Appendix II). Therefore, the savings associated with alleviation of harbor sedimentation alone offset about a third of the costs of construction site measures. Savings for Los Angeles Harbor will be about $3 million per year. Regional savings will be about $10 million, with a present worth of $330 million.

To cite another example, it is estimated that the San Joaquin Marsh wetland preserve collects 50,000 tons of sediment per year. Assuming a removal cost of $30 per ton, the benefit for Newport Bay, which is just downstream, is $1.5 million per year.

*Cost Savings from Improved Public Health*

Sufficient data do not exist for estimating the value of benefits from reduced exposure to air pollutants. Certainly fine particles are an important part of the causes of health impairment, and experts agree that resuspension of road dust is an important contributor to fine particle exposure at street level where we live. They also contribute substantially to settlement of dust and dirt on buildings, requiring cleaning expenses. However, estimates of the magnitude of this effect are not currently possible.

*Summary of predicted costs and benefits*

Table 3 presents a summary of the estimated costs and benefits. Three estimates are included. In the first (A), non-structural BMPs are presumed to be the only measures employed. In the second (B), wetlands and infiltration basins are assumed, and the costs are estimated on a cost-per-square-mile basis. The third set of columns (C) again describes the wetlands and infiltration basins scenario, but makes cost estimates on a per-acre-foot-detention basis. The second and third estimates also presume implementation of the non-structural BMPs, except for storm drain cleaning.

Benefits differ because implementation on non-structural BMPs does not produce property increases associated with greenspace, does not significantly increase groundwater supply, and does not reduce harbor sedimentation.

The costs of stormwater quality control are significant. Non-structural BMPs alone will cost $2.6 billion. Structural systems, including wetlands and infiltration basins, will cost between $5.7 billion and $7.4 billion. However, it should be noted that these costs will be borne over a period of many years—probably ten years at least. More importantly, the benefits of these expenditures considerably exceed their costs. For the non-structural BMPs alone, the benefit-to-cost ratio is 1.9. For the structural approach the estimates are 2.5 and 3.3. Control of pollution and reestablishment of the hydrologic cycle will produce a greener city with higher property values, better esthetics, cleaner rivers and a cleaner ocean, and a larger and more stable water supply.

**Table 2. Overall Cost Estimate for Stormwater Quality Control in the Los Angeles Region**

Sums are rounded to two significant figures

| | | A. Non-Structural BMPs, modified from APWA | | | B. Wetlands and Infiltration Basins, watershed area basis | | C. Wetlands and Infiltration Basins, detention volume basis | | |
|---|---|---|---|---|---|---|---|---|---|
| **Regions and BMPs** | **Area, sq. miles** | **Capital Cost $M** | **O&M Costs $M** | **Total $M** | **Cost / square mile, $M** | **Cost or Benefit $M** | **Acre-feet initial flow** | **Cost per acre-foot** | **Cost or Benefit, $M** |
| **Costs for Non-Structural BMPs** | | | | | | | | | |
| No Littering Ordinance | | 2.5 | 3 | 103 | | 103 | | | 103 |
| Pet Waste Ordinance | | 2.5 | 3 | 103 | | 103 | | | 103 |
| Chemical Use and Storage | | 2.5 | 3 | 103 | | 103 | | | 103 |
| Public Education | | | 5 | 50 | | 50 | | | 50 |
| Illicit Discharge Program | | 6.5 | 80 | 407 | | 407 | | | 407 |
| Increased Cleaning of Drains | | | 27 | 900 | | | | | |
| Trash Control | | | | 608 | | 608 | | | 608 |
| Low Flow Sanitary Treatment | | | | 28 | | 28 | | | 28 |
| Improved Street Cleaning | 2050 | | | 250 | | 250 | | | 250 |
| Private On-site BMPs | | 241 | | 241 | | 241 | | | 241 |
| New construction rules | | | | Mod-est | | Mod-est | | | Mod-est |
| *Total N-S BMPs* | | | | 2791 | | 1891 | | | 1891 |
| **Costs for Structural BMPs** | | | | | | | | | |
| Rural | 1050 | | | | | 0 | | | 0 |
| Low Density, Industrial (C=0.4) | 1000 | | | | 0.42 | 420 | 15,500 | 0.053 | 822 |
| High Density (C=0.6) | 1000 | | | | 3.70 | 3,700 | 23,250 | 0.098 | 2,279 |
| Extremely Dense (C=1.0) | 50 | | | | 33.00 | 1,650 | 1,938 | 0.470 | 911 |
| *Total Facilities Costs* | | | | | | 5,770 | | | 4,011 |
| *Total Cost, LA Region* | | | | **2550** | | **7420** | | | **5661** |
| **Benefits** | | | | | | | | | |
| Flood Control | | | | | | 400 | | | 400 |
| Greenspace, Water Property Values | | | | | | 5,000 | | | 5,000 |
| Clean Ocean Esthetics | | | | 2500 | | 2,500 | | | 2,500 |
| Clean Streets Esthetics | | | | 950 | | 950 | | | 950 |
| Groundwater Replenishment | | | | | | 7,200 | | | 7,200 |
| Improved Beach Tourism | | | | 100 | | 100 | | | 100 |
| Preservation of Ocean Ecosystems | | | | 2000 | | 2,000 | | | 2,000 |
| Reduced Harbor Sedimentation | | | | | | 330 | | | 330 |
| Improved Health, Cleaner Buildings, Reduced Exposure to Particulates | | | | | | Sig-nifican t | | | Sig-nifican t |
| *Total Benefits, LA Region* | | | | **5600** | | **18,000** | | | **18,000** |

**Recommendations for Action**

The results developed here indicate that a distributed approach to stormwater quality control, employing non-structural BMPS with a system of wetlands and infiltration basins will achieve stormwater quality compliance and will be far cheaper than advanced treatment plants. It is recommended that the responsible organizations begin immediately with the non-structural measures, analyze their effectiveness, and add wetlands and infiltration systems as necessary to achieve the goal of protecting the rivers and coastal zones of the Los Angeles Region. Our results indicate that the benefit-to-cost ratio for the non-structural BMPs is about two, and for the larger effort is about 3. Thus both the beginning effort and the full response represent good investments for the people of the region.

*Outreach*

Municipalities that are finding themselves responsible for stormwater cleanup should act immediately to lay the groundwork for comprehensive programs. Outreach programs should be developed to inform the public of the problems and of what they can do to help with the solution. Vigorous efforts to reduce littering, for example, will reduce costs in subsequent steps as programs develop. Current regulations controlling release of sediments from construction sites should be enforced and supplemented with contractor education efforts.

*Data Collection and Planning*

Municipalities should immediately begin the process of determining the extent and nature of their individual stormwater quality problems. Many may find, for example, that stormwater from neighborhoods of single-family homes can be discharged to rivers or infiltrated with little or no treatment. Early identification and elimination of problem sources might greatly reduce later expenditures on treatment systems—the programs of thorough data collection and vigorous enforcement described earlier were notably effective at reducing pollutant concentrations in discharges and cost very little. It will certainly be a tragedy if we build expensive treatment systems to solve a problem that can be eliminated with a citation.

Municipalities should also immediately assess their property holdings. Cities frequently own substantial amounts of land, and some of this will be appropriate for stormwater control facilities. Purchasing programs should be developed immediately, so that cities can take advantage of opportunities for economical land acquisition as they arise.

*Administrative Structure*

Adding to the daunting technical and financial problems, the distributed approach for stormwater control requires that problems be solved by a holistic effort for each sub-watershed. The boundaries of sub-watersheds do not correspond to political boundaries, and cities will be forced to cooperate in ways that have never been required before. Further, controlling local pollution releases and restoring the hydrologic cycle involve issues that have traditionally be dealt with by an astonishing variety of agencies. If we imagine controlling the runoff quality of a sub-watershed by installing a park/infiltration system with associated wetlands, for example, efforts should include the sanitation districts for the cities overlapping the sub-watershed (because of stormwater quality control), the Water Replenishment District (because of groundwater infiltration), the County Flood Control District (because the park will contribute to flood control and reduce the cost of downstream facilities), parks departments (because a recreational area will result), and wildlife agencies (governing the habitat created). It is reasonable to expect, moreover, that each of these agencies will contribute to the funding necessary for construction and maintenance. It is likely that, with appropriate apportionment, such a facility will have a favorable cost/benefit ratio for each of the agencies involved. It is certain that gaining the cooperation and contributions of all of these agencies will be extremely difficult. It may be appropriate that legislation be passed at the state level to provide a means for bringing these agencies together.

*Funding*

While runoff quality can be controlled by methods significantly cheaper than the massive construction of advanced treatment plants, the cost remains significant, and comes at a time when state and local governments are desperately short of funds. It is reasonable to suggest that funding should come from those who contribute to the problem, so that the taxation system mimics a market—assigning costs to the activity that generates them. Hundreds of municipal stormwater utilities, for example, have instituted a tax that is proportional to the number of square feet of impermeable surface on the land. An extension to this approach is to give property-owners fee rebates for installing BMPs that lower runoff quantity or increase water quality. This approach, or others that encourage owners to reduce their runoff, could fund the solution even as they reduce the magnitude of the problem. Certainly fines for littering should be used to fund litter law enforcement in the way that parking fines fund parking enforcement. Efforts to control illegal discharges could be at least partially supported by fines of those making the discharges. All of these approaches would be consistent with the principle that the polluter should pay, and would provide incentives that would contribute to stormwater cleanup.

A "cap and trade" system would be one means of approaching the funding dilemma. If all landowners were given the choice of either purchasing tradable discharge allowances or cleaning up runoff, a free-market trading system would allow owners to trade these allowances and in the process assign stormwater runoff reduction to owners who are able to cheaply install BMPs. This system, or a combined stormwater utility fee with BMP credits, would tend to produce the lowest cost solution overall. A study under way in Cincinnati, Ohio, suggests that such systems could be successful (Thurston et al., 2003).

*Changes in Building Codes*

This study indicates that parking lots constitute a significant resource for promoting stormwater infiltration. Building codes should be amended immediately to require that all new or reconstructed parking lots be designed to infiltrate the water that they collect. While there will be costs associated with the infiltration systems, the work described above indicates that much—and often all—of these costs can be offset by reduced costs for curbs and drainage systems.

Very large facilities, such as those for malls, should be considered sites for installation of subsurface infiltration vaults that could receive water from surrounding areas as well. These could be installed in sections, to minimize disruption to the commercial establishments. A mechanism could be established by which the site owners are compensated for the costs of handling the runoff.

Other building codes should be changed to encourage on-site infiltration of water rather than rapid drainage to the street. It may also be appropriate to consider limitations on the use of architectural copper sheeting, which can release copper ions to stormwater, and on the use of galvanized materials, which can release zinc.

*Purchase of High-Efficiency Street Sweeping Equipment*

Improved street sweeping seems very likely to be an important part of future stormwater programs. It can remove 30 to 50 percent of the particulate-associated pollutants, substantially reducing the load on downstream systems. It will have the secondary benefits of improving neighborhood appearance and reducing the exposure to air pollutants at street level. Municipalities should make the decision now to purchase only high-efficiency vacuum sweepers as they make routine replacements of their street cleaning machinery.

*Investigation of Coliform Sources*

Additional studies, particularly employing newly available methods for rapid identification of microorganisms, should be done to determine the sources of pathogenic organisms in stormwater.

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# APPENDIX I.
# BEST MANAGEMENT PRACTICES FOR CONSTRUCTION SITES

(Adapted from the Washington State Department of Ecology Water Quality Program, 2001).

The **12 Elements** of Storm Water Pollution Prevention Plan (SWPPP):

**Mark Clearing Limits**

Prior to beginning land disturbing activities all clearing limits, sensitive areas and their buffers, and trees that are to be preserved shall be clearly marked, both in the field and on the plans, to prevent damage and offsite impacts.

*Preserving Natural Vegetation*
The purpose of preserving natural vegetation is to reduce erosion wherever practicable. Limiting site disturbance is the single most effective method for reducing erosion.

*Buffer Zones*
An undisturbed area or strip of natural vegetation or an established suitable planting will provide a living filter to reduce soil erosion and runoff velocities.

*High Visibility Plastic or Metal Fence, Stake and Wire Fence*
Fencing is intended to: (1) restrict clearing to approved limits; (2) prevent disturbance of sensitive areas, their buffers; (3) limit construction traffic to designated construction entrances or roads; and, (4) protect areas where marking with survey tape may not provide adequate protection.

**Establish Construction Access**

To minimize the tracking of sediment onto public roads and into surface waters:

*Stabilized Construction Entrance*
Construction entrances are stabilized to reduce the amount of sediment transported onto paved roads by vehicles or equipment by constructing a stabilized pad of quarry spalls at entrances to construction sites.

*Wheel Wash*
Wheel washes reduce the amount of sediment transported onto paved roads by motor vehicles.

*Construction Road/Parking Area Stabilization*

Stabilizing subdivision roads, parking areas, and other onsite vehicle transportation routes immediately after grading reduces erosion caused by construction traffic or runoff.

**Control Flow Rates**

Properties and waterways downstream from development sites shall be protected from erosion due to increases in the volume, velocity, and peak flow rate of stormwater runoff from the project site.

*Sediment Trap*
A sediment trap is a small temporary ponding area with a gravel outlet used to collect and store sediment from sites cleared and/or graded during construction.

*Temporary Sediment Pond*
Sediment ponds remove sediment from runoff originating from disturbed areas of the site. Sediment ponds are typically designed to remove sediment no smaller than medium silt (0.02 mm).

**Install Sediment Controls**

*Straw Bale Barrier*
~~To decrease the velocity of sheet flows and intercept and detain small amounts~~ of sediment from disturbed areas of limited extent, preventing sediment from leaving the site.

*Brush Barrier*
The purpose of brush barriers is to reduce the transport of coarse sediment from a construction site by providing a temporary physical barrier to sediment and reducing the runoff velocities of overland flow.

*Gravel Filter Berm*
A gravel filter berm is constructed on rights-of-way or traffic areas within a construction site to retain sediment by using a filter berm of gravel or crushed rock.

*Silt Fence*
Use of a silt fence reduces the transport of coarse sediment from a construction site by providing a temporary physical barrier to sediment and reducing the runoff velocities of overland flow.

*Vegetated Strip*
Vegetated strips reduce the transport of coarse sediment from a construction site by providing a temporary physical barrier to sediment and reducing the runoff velocities of overland flow.

*Straw Wattles*

Straw wattles are temporary erosion and sediment control barriers consisting of straw that is wrapped in biodegradable tubular plastic or similar encasing material. They reduce the velocity and can spread the flow of rill and sheet runoff, and can capture and retain sediment.

*Sediment Trap*

A sediment trap is a small temporary ponding area with a gravel outlet used to collect and store sediment from sites cleared and/or graded during construction.

*Temporary Sediment Pond*

Sediment ponds remove sediment from runoff originating from disturbed areas of the site. Sediment ponds are typically designed to remove sediment no smaller than medium silt (0.02 mm).

*Construction Stormwater Chemical Treatment*

Turbidity is difficult to control once fine particles are suspended in stormwater runoff from a construction site. Sedimentation ponds are effective at removing larger particulate matter by gravity settling, but are ineffective at removing smaller particulates such as clay and fine silt. Sediment ponds are typically designed to remove sediment no smaller than medium silt (0.02 mm). Chemical treatment may be used to reduce the turbidity of stormwater runoff.

*Construction Stormwater Filtration*

Filtration removes sediment from runoff originating from disturbed areas of the site.

**Stabilize Soils**

Exposed and unworked soils shall be stabilized by application of effective BMPs that protect the soil from the erosive forces of raindrops, flowing water, and wind.

*Temporary and Permanent Seeding*

Seeding is intended to reduce erosion by stabilizing exposed soils. A well-established vegetative cover is one of the most effective methods of reducing erosion.

*Mulching*

The purpose of mulching soils is to provide immediate temporary protection from erosion. Mulch also enhances plant establishment by conserving moisture, holding fertilizer, seed, and topsoil in place, and moderating soil temperatures.

*Nets and Blankets*

Erosion control nets and blankets are intended to prevent erosion and hold seed and mulch in place on steep slopes and in channels so that vegetation can become well established. In addition, some nets and blankets can be used to permanently reinforce turf to protect drainage ways during high flows.

*Plastic Covering*

Plastic covering provides immediate, short-term erosion protection to slopes and disturbed areas.

*Sodding*

The purpose of sodding is to establish permanent turf for immediate erosion protection and to stabilize drainage ways where concentrated overland flow will occur.

*Topsoiling*

Addition of topsoil will provide a suitable growth medium for final site stabilization with vegetation. While not a permanent cover practice in itself, topsoiling is an integral component of providing permanent cover in those areas where there is an unsuitable soil surface for plant growth. Native soils and disturbed soils that have been organically amended not only retain much more stormwater, but they also serve as effective biofilters for urban pollutants and, by supporting more vigorous plant growth, reduce the water, fertilizer and pesticides needed to support installed landscapes. Topsoil does not include any subsoils but only the material from the top several inches, including organic debris.

*Polyacrylamide for Soil Erosion Protection*

Polyacrylamide (PAM) is used on construction sites to prevent soil erosion. Applying PAM to bare soil in advance of a rain event significantly reduces erosion and controls sediment in two ways. First, PAM increases the soil's available pore volume, thus increasing infiltration through flocculation and reducing the quantity of stormwater runoff. Second, it increases flocculation of suspended particles and aids in their deposition, thus reducing stormwater runoff turbidity and improving water quality.

*Surface Roughening*

Surface roughening aids in the establishment of vegetative cover, reduces runoff velocity, increases infiltration, and provides for sediment trapping through the provision of a rough soil surface.

*Gradient Terraces*

Gradient terraces reduce erosion damage by intercepting surface runoff and conducting it to a stable outlet at a non-erosive velocity.

*Dust Control*

Dust control prevents wind transport of dust from disturbed soil surfaces onto roadways, drainage ways, and surface waters.

*Small Project Construction Stormwater Pollution Prevention*

To prevent the discharge of sediment and other pollutants to the maximum extent practicable from small construction projects.

**Protect Slopes**

Design, construct, and phase cut and fill slopes in a manner that will minimize erosion, considering soil type and its potential for erosion.

*Temporary and Permanent Seeding*

Seeding is intended to reduce erosion by stabilizing exposed soils. A well-established vegetative cover is one of the most effective methods of reducing erosion.

*Surface Roughening*

Surface roughening aids in the establishment of vegetative cover, reduces runoff velocity, increases infiltration, and provides for sediment trapping through the provision of a rough soil surface.

*Gradient Terraces*

Gradient terraces reduce erosion damage by intercepting surface runoff and conducting it to a stable outlet at a non-erosive velocity.

*Interceptor Dike and Swale*

Provide a ridge of compacted soil, or a ridge with an upslope swale, at the top or base of a disturbed slope or along the perimeter of a disturbed construction area to convey stormwater. Using the dike and/or swale to intercept the runoff from unprotected areas and direct it to areas where erosion can be controlled. This can prevent storm runoff from entering the work area or sediment-laden runoff from leaving the construction site.

*Grass-Lined Channels*

Channels lined with grass can convey runoff without erosion, and will provide some degree of treatment and infiltration.

*Pipe Slope Drains*

Piping can be used to convey stormwater anytime water needs to be diverted away from or over bare soil to prevent gullies, channel erosion, and saturation of slide-prone soils.

*Subsurface Drains*

Drains below the surface can intercept, collect, and convey ground water to a satisfactory outlet. These can be a perforated pipe or conduit below the ground surface. The perforated pipe provides a dewatering mechanism to drain excessively wet soils, provide a stable base for construction, improve stability of structures with shallow foundations, or to reduce hydrostatic pressure to improve slope stability.

*Level Spreader*

To provide a temporary outlet for dikes and diversions consisting of an excavated depression constructed at zero grade across a slope. To convert concentrated runoff to sheet flow and release it onto areas stabilized by existing vegetation or an engineered filter strip.

*Check Dams*

Construction of small dams across a swale or ditch reduces the velocity of concentrated flow and dissipates energy at the check dam.

*Triangular Silt Dike (Geotextile-Encased Check Dam)*

Triangular silt dikes may be used as check dams, for perimeter protection, for temporary soil stockpile protection, for drop inlet protection, or as a temporary interceptor dike.

**Protect Drain Inlets**

Storm drain inlets operable during construction shall be protected so that stormwater runoff does not enter the conveyance system without first being filtered or treated to remove sediment.

*Storm Drain Inlet Protection*

To prevent coarse sediment from entering drainage systems prior to permanent stabilization of the disturbed area:

**Stabilize Channels And Outlets**

Temporary on-site conveyance channels shall be designed, constructed, and stabilized to prevent erosion from the expected flow velocity of a 2-year, 24-hour frequency storm for the developed condition.

*Channel Lining*

Lining will protect erodible channels by providing a channel liner using either blankets or riprap.

*Outlet Protection*

Outlet protection prevents scour at conveyance outlets and minimizes the potential for downstream erosion by reducing the velocity of concentrated stormwater flows.

**Control Pollutants**

All pollutants, including waste materials and demolition debris, that occur on site during construction shall be handled and disposed of in a manner that does not cause contamination of stormwater.

*Concrete Handling*

Concrete work can generate process water and slurry that contain fine particles and high pH, both of which can violate water quality standards in the receiving water. Concrete handling is intended to minimize and eliminate concrete process water and slurry from entering waters of the state.

*Sawcutting and Surfacing Pollution Prevention*

Sawcutting and surfacing operations generate slurry and process water that contain fine particles and high pH (concrete cutting), both of which can violate the water quality standards in the receiving water. Collection of this water is intended to minimize and eliminate process water and slurry from entering waters of the State.

### Control De-Watering

Foundation, vault, and trench de-watering water shall be discharged into a controlled conveyance system prior to discharge to a sediment pond.

### Maintain BMPs

Temporary and permanent erosion and sediment control BMPs shall be maintained and repaired as needed to assure continued performance of their intended function. Maintenance and repair shall be conducted in accordance with BMPs.

### Manage the Project

Development projects shall be phased where feasible in order to prevent, to the maximum extent practicable, the transport of sediment from the development site during construction. Revegetation of exposed areas and maintenance of that vegetation shall be an integral part of the clearing activities for any phase.

## APPENDIX II. ESTIMATION OF COSTS FOR CONTROLLING SEDIMENT RELEASES AT CONSTRUCTION SITES

EPA described the costs of the Phase II program in Chapter 4 of the economic analysis (U.S. EPA, 1995). This appendix is a summary of that description, and the figures presented come from that document. The costs were divided into 4 categories: municipal costs, construction costs, federal costs and state costs. Each of these was considered separately.

Construction costs:

Construction costs were described in parts 4-8 to 4-25. All the cost calculations are based on 1998 dollar value.

Because the Phase II program targets construction areas of 1 to 5 acres of land, the cost analysis are done for these land sizes. EPA divided the construction costs into two parts. The first part requires the owners and operators of construction sites disturbing one to five acres of land to plan and implement erosion and sediment control BMPs. The second part requires the implementation of post-construction stormwater runoff controls on construction sites located in Phase II municipalities.

*Erosion and sediment control costs*

EPA developed a national level cost estimate for implementing erosion and sediment controls on sites that disturb between one and 5 acres. EPA estimated a per site compliance cost for sites of one, three, and five acres and multiplied the cost by the total number of Phase II construction starts expected to incur incremental cost in these size categories to obtain a national cost estimate. EPA used construction start data from fourteen municipalities and 1994 Census Bureau construction permit data to estimate the number of construction starts disturbing between one and five acres of land. Of the estimated 129,675 construction starts likely to incur incremental costs, EPA expects that 110,223 (85%) will require erosion and sediment controls to comply with the regulation.

Exhibit 4–4. Summary Characteristics of Municipalities Where Construction Start Data was Collected

| Municipality | Population 1996 (Estimates)[1] | Population Growth 1990 to 1996 | Median Household Income (1989) | Area (Sq. Mi.) |
|---|---|---|---|---|
| Austin, TX | 541,278 | +14.7% | $25,414 | 217.8 |
| Baltimore County, MD | 720,662 | +4.1% | $38,837 | 599.0 |
| Cary, NC | 75,676 | +70.5% | $46,259 | 31.2 |
| Fort Collins, CO | 104,196 | +19.1% | $28,826 | 41.2 |
| Lacey, WA | 27,381 | +42.0% | $29,726 | 10.1 |
| Loudoun County, VA | 133,493 | +54.9% | $52,064 | 520.0 |
| New Britain, CT | 71,512 | –5.3% | $30,121 | 13.3 |
| Olympia, WA | 39,006 | +15.6% | $27,785 | 16.1 |
| Prince George's County, MD | 770,633 | +5.6% | $43,127 | 486.0 |
| Raleigh, NC | 243,835 | +15.0% | $32,451 | 88.1 |
| South Bend, IN | 102,100 | –3.2% | $24,131 | 36.4 |
| Tallahassee, FL | 136,751 | +9.6% | $34,764 | 63.3 |
| Tucson, AZ | 449,002 | +9.1% | $21,748 | 156.3 |
| Waukesha, WI | 60,197 | +5.8% | $36,192 | 17.3 |
| United States | 265 million | +6.6% | $35,225 | |

*Source:* US Department of Commerce, Bureau of the Census. [http://www.census.gov].
[1] US Census Bureau Data (1996).

### Per-Site Compliance Costs: Installation and O&M.

EPA used standard cost estimates from R.S. Means (R.S. Means, 1997a and 1997b) and the WEF database to estimate construction BMP costs for 27 model sites of typical site conditions in the United States. The model sites included three different site sizes (one, three, and five acres), three slope variations (3%, 7%, and 12%), and three soil erosivity conditions (low, medium, and high). EPA used the WEF database to determine BMP combinations appropriate to the model site conditions. For example, sites with shallow slopes and a low erosivity require few BMPs, while larger, steeper, and more erosive sites required more BMPs. Detailed site plans, assumptions, and BMPs that could be used are presented in Appendices B–2 and B–3. Based on the assumption that any combination of site factors is equally likely to occur on a given site, EPA averaged the matrix of estimated costs to develop an average cost for one-, three-, and five-acre starts for all soil erodibilities and slopes.

Exhibit 4–6. BMPs Used for the Model Sites

| Site Size (acres) | Soil Erodibility | Slope | | |
|---|---|---|---|---|
| | | 3% | 7% | 12% |
| 1 | low | a | a,b | a,c,e |
| | med | a,b | a,c,e | a,c,e |
| | high | a,c,e | a,c,e | c,e,f,g1 |
| 3 | low | a,b | a,c,e | c,d,e,f,g2 |
| | med | a,c,e | a,c,e | c,d,e,f,g2 |
| | high | a,c,e | c,d,e,f,g2 | c,d,e,f,g2 |
| 5 | low | a,c,d,e | c,d,e,f,g3 | c,d,e,f,g3 |
| | med | a,c,d,e | c,d,e,f,g3 | c,d,e,f,g3 |
| | high | c,d,e,f,g3 | c,d,e,f,g3 | c,d,e,f,g3 |

a = silt fence
b = mulch
c = seed and mulch
d = stabilized construction entrance
e = stone check dam
f = earthen dike directing runoff to sediment trap
g = sediment trap (1=1,800 cf, 2=5,400 cf, 3=9,000 cf)

Costs related to each BMP and the description of the BMP were shown in Exhibit 4-7 of the original document.

Exhibit 4–8. Estimated Cost of BMPs for the Model Sites (1998 dollars)

| Site Size (acres) | Soil Erodibility | Cost by Slope | | | Average Cost |
|---|---|---|---|---|---|
| | | 3% | 7% | 12% | |
| 1 | low | $317 | $814 | $1,422 | $1,206 |
| | med | $814 | $1,422 | $1,422 | |
| | high | $1,422 | $1,422 | $1,799 | |
| 3 | low | $1,978 | $3,804 | $6,047 | $4,598 |
| | med | $3,804 | $3,804 | $6,047 | |
| | high | $3,804 | $6,047 | $6,047 | |
| 5 | low | $6,245 | $9,334 | $9,519 | $8,709 |
| | med | $6,245 | $9,334 | $9,519 | |
| | high | $9,334 | $9,334 | $9,519 | |

**Per-Site Compliance Costs: Administrative.**

EPA then estimated administrative costs per construction site for the following elements required under the Phase II rule: submittal of a notice of intent (application) for permit coverage; notification to municipalities; development of a stormwater pollution prevention plan (SWPPP); record retention; and submittal of a notice of termination. The average total administrative cost per site was estimated to be $937.

Exhibit 4–10. Estimated Other Administrative Phase II Construction Costs Per Site (1998 Dollars)

| Administrative Requirement | Cost |
|---|---|
| NOI | $126.50 |
| Municipal Notification | $17.10 |
| SWPPP | $772.25 |
| Record Retention | $4.51 |
| NOT | $17.10 |
| Estimated Total Cost (per site) | $937.46 |

Summing the average BMP costs and the administrative costs yields a total compliance cost of $2,143 for sites disturbing between one and two acres of land, $5,535 for sites disturbing between two and four acres of land, and $9,646 for sites disturbing between four and five acres of land. To estimate national level incremental annual costs for Phase II construction starts, EPA multiplied the total costs of compliance for one to two acre, two to four acre, and four to five acre sites by the total number of Phase II construction starts within each of those size categories. This yielded an estimated annual compliance cost of approximately $499.8 million (based on 110,223 construction starts in 1998).

EPA anticipates that 19,452 (15%) of the estimated Phase II incremental construction universe will qualify for a waiver from program requirements by meeting one of two conditions. Construction sites can be waived if they are either located in areas with low rainfall potential or if water quality analyses show that there is no need for regulation. EPA estimates the incremental administrative cost associated with preparing and submitting a waiver to be approximately $665,000 (1998). Total costs (national compliance and waiver costs) resulting from implementation of the Phase II erosion and sediment control provision are estimated to be **$500.4 million.**

Exhibit 4–11. Estimated National Phase II Construction Compliance Costs by Climatic Zones for Year 1998 (1998 Dollars)

| Climatic Zone | Representative City | Number of Starts 1–2 Acres | Number of Starts 2–4 Acres | Number of Starts 4–5 Acres | Total Starts | Costs for Starts 1–2 Acres | Costs for Starts 2–4 Acres | Costs for Starts 4–5 Acres | Total Costs |
|---|---|---|---|---|---|---|---|---|---|
| A | Portland, OR | 1,683 | 1,471 | 659 | 3,813 | $3,608,528 | $8,141,052 | $6,360,054 | $18,356,897 |
| B | Boise, ID | 1,508 | 1,345 | 576 | 3,429 | $3,232,932 | $7,443,548 | $5,556,280 | $16,455,088 |
| C | Fresno, CA | 2,388 | 2,018 | 974 | 5,380 | $5,118,068 | $11,171,812 | $9,400,679 | $26,039,422 |
| D | Las Vegas, NV | 7,154 | 6,256 | 3,035 | 16,445 | $15,335,047 | $34,628,344 | $29,276,500 | $80,306,157 |
| E | Denver, CO | 1,787 | 1,613 | 636 | 4,036 | $3,829,714 | $8,928,128 | $6,135,764 | $18,893,606 |
| F | Bismarck, ND | 560 | 469 | 156 | 1,185 | $1,199,916 | $2,595,370 | $1,508,877 | $5,304,163 |
| G | Helena, MT | 1,067 | 921 | 348 | 2,336 | $2,287,796 | $5,098,377 | $3,354,650 | $10,740,823 |
| H | Amarillo, TX | 3,295 | 2,838 | 1,152 | 7,285 | $7,063,767 | $15,708,383 | $11,110,516 | $33,882,666 |
| I | San Antonio, TX | 1,105 | 960 | 414 | 2,479 | $2,368,045 | $5,314,569 | $3,997,033 | $11,679,647 |
| K | Duluth, MN | 2,957 | 1,796 | 326 | 5,078 | $6,339,106 | $9,939,565 | $3,141,089 | $19,419,760 |
| M | Des Moines, IA | 9,335 | 7,599 | 2,695 | 19,629 | $20,009,581 | $42,063,182 | $26,002,165 | $88,074,928 |
| N | Nashville, TN | 5,801 | 4,707 | 1,705 | 12,212 | $12,434,357 | $26,052,990 | $16,445,128 | $54,932,475 |
| P | Atlanta, GA | 5,157 | 2,956 | 1,127 | 9,241 | $11,054,430 | $16,364,835 | $10,875,252 | $38,294,517 |
| R | Hartford, CT | 6,909 | 5,324 | 2,116 | 14,348 | $14,808,848 | $29,468,120 | $20,412,901 | $64,689,869 |
| T | Charleston, SC | 1,194 | 675 | 263 | 2,132 | $2,560,342 | $3,736,824 | $2,535,496 | $8,832,662 |
| V | Hawaii | 504 | 423 | 218 | 1,145 | $1,080,648 | $2,340,928 | $2,099,447 | $5,521,023 |
| W,X,Y | Alaska | 22 | 20 | 8 | 50 | $47,885 | $112,127 | $72,563 | $232,575 |
| Total | | 52,426 | 41,389 | 16,408 | 110,223 | $112,379,010 | $229,108,154 | $158,284,394 | $499,771,558 |

*Note:* Number of sites include only those where storm water BMPs are not currently required by Federal or State programs. Totals may not add because of rounding.

Exhibit 4–12. Phase II Erosion and Sediment Control Annual Costs

| Construction Costs | Universe | Estimated Total National Annual Costs (1998 dollars) |
|---|---|---|
| Compliance Costs | 110,223 | $499,771,558 |
| Waiver Costs* | 19,452 | $665,064 |
| Total | 129,675 | $500,436,622 |

*Based on an engineering assistant's wage of $34.19 per hour. U.S. Department of Labor, 1996.

EPA also estimated incremental costs attributable to the post-construction runoff control measures. The Phase II municipal program requires municipalities to develop, implement, and enforce a program that addresses stormwater runoff from new development and redevelopment sites on which land disturbance is greater than one acre and that discharge into a regulated MS4. To develop a cost estimate associated with this measure, EPA estimated a per site BMP cost, including operation and maintenance, for 12 model sites of varying size (1, 3, 5, and 7 acres) and imperviousness (35%, 65%, and 85%). The per site BMP cost was then multiplied by the total number of multi-family, institutional, and commercial construction starts that are located in Phase II urbanized areas to obtain a national cost estimate. Using this total of 13,364 postconstruction starts, EPA estimated a range of national costs associated with this measure from $44.6 to $178.3 million (see Appendix B–4). EPA estimates total annual costs to construction operators, including implementation of erosion and sediment controls and post-construction controls, to be between **$545.0 – $678.7 million.**

Exhibit 4–15. Estimated Post-Construction Runoff Control Costs

| Area | 35% Impervious (Multi-Family Residential) | 65% Impervious (Multi-Family/ Commercial/ Institutional) | 85% Impervious (Commercial) | Total Cost (1998 dollars) |
|---|---|---|---|---|
| 1 Acre | $503,163 | $14,318,035 | $25,530,478 | $40,351,676 |
| 3 Acres | $1,486,961 | $29,571,535 | $29,588,931 | $60,647,426 |
| 5 Acres | $2,001,641 | $11,835,630 | $9,151,038 | $22,988,309 |
| 7 Acres | $3,863,272 | $23,910,571 | $26,494,414 | $54,268,258 |
| Total Cost | $7,855,037 | $79,635,771 | $90,764,861 | $178,255,669 |

Summary of results of the total costs of the phase II program are shown below:

Exhibit 4–21. Potential Annual Costs for Phase II Storm Water Regulation

| Phase II Element | Universe | Estimated Total National Annual Costs (1998 dollars) |
|---|---|---|
| Municipal | 32,458,000 Households | $297,318,623 |
| Construction | 129,675 Erosion & Sediment Control Starts and 13,364 Post-Construction Starts | $545,000,539 – $678,692,291 |
| Federal and State | 53 States and Territories | $5,318,668 |
| Total | | $847,637,830 – $981,329,582 |

**Reduced Sediment Delivery From Construction Starts:**

To estimate reduced sediment delivery from Phase II construction starts, the US ACE developed a model based on EPA's 27 model sites to estimate sediment loads from construction starts with and without Phase II controls (US ACE, 1998). The US ACE model uses the construction site version of the Revised Universal Soil Loss Equation (RUSLE) to generate sediment delivery estimates for 15 climatic regions with each of the following variations: three site sizes (one, three, and five acres), three soil erodibility levels (low, medium, and high), three slopes (3%, 7%, and 12%), and the BMP combinations from EPA's 27 model sites. The 15 climatic regions represent the various rainfall and temperature conditions throughout the United States. Sediment delivery represents the quantity of sediment that BMPs placed at the base of the hill slope are unable to capture. EPA estimated that the average reduction in soil loss from the model sites implementing BMPs would be 89.6 tons per site. (Calculations in Exhibit 4-24)

To determine the reduction in soil loss using the estimated 80% effectiveness rate, EPA multiplied the weighted average soil loss per start (89.6 tons) by 80%. This resulted in an estimated reduction in soil loss of 71.7 tons per site. Multiplying this reduction by the 110,223 construction starts expected to implement erosion and sediment controls for the year 1998, results in an estimated 7.9 million ton reduction in soil loss annually.

Exhibit 4–25. National Reduction Estimates for Municipalities and Construction Starts (tons/year)

| Phase II Element | 20% Reduction | 80% Reduction |
|---|---|---|
| Municipal TSS Loading | 639,115 | 4,062,815 |
| Soil loss from Construction Sites | 1,975,196 | 7,900,785 |

**Summary**

EPA has not presented the total cost of prevention of sediments leaving the site per ton of the sediment. ES.11 (in executive summary) describes only the costs effectiveness related to the Municipal TSS loading reduction. It seems that by a simple calculation from the two former exhibits (4-24 and 4-25) that the total cost assuming 80% reduction in the sediments would be between $69 - $86 per ton of sediment.

# MEMORANDUM

OFFICE OF WATER PROGRAMS
C S U SACRAMENTO
7801 Folsom Boulevard, Suite 102
Sacramento, CA 95826

*Date:* **August 15, 2003**
*To:* **Pamela Barksdale, State Water Resource Control Board**
*From:* **Brian Currier**
*Subject:* **Scope for the storm water cost survey**

This memorandum presents additional information and recommendations in order to proceed with Task A of the "Survey of Costs to Develop, Implement, Maintain and Monitor Municipal Separate Storm Sewer System (MS4) Stormwater Management Programs (SWMP) and Description of Alternatives for Control of Stormwater Quality in Los Angeles County" (See Attachment A). A presentation of candidate municipalities, corresponding demographics, and recommendations for the six municipalities to be surveyed are presented herein.

*Nomination of Municipalities*

The identification of candidate municipalities began with a conference call on June 23, 2003 with the State Water Resources Control Board and representatives from interested Regional Water Quality Control Boards. The scope and intent of the study was shared with the conference call participants. The Regional Boards then nominated municipalities within their jurisdiction that appear are complying with their permits and are taking appropriate steps toward meeting water quality objectives. Some nominees were subsequently eliminated upon further discussion with either the municipality or the regional board. The remaining municipalities are presented in Table 1 along with a limited set of city characteristics.

**Table 1. Nominated Municipalities for the Stormwater Cost Survey**

| CITY | TOTAL POPULATION | AREA (Sq. Miles) | MEDIAN INCOME/ HOUSEHOLD ($) | MEAN INCOME ($) | INCOME DENSITY ($/ft$^2$) | STORM WATER DRAINAGE SYSTEM FUND |
|---|---|---|---|---|---|---|
| **CALIFORNIA** | 33,871,648 | 163,696 | 47,493 | 22,711 | 0.2 | |
| Los Angeles | 3,694,820 | 498 | 36,687 | 20,671 | 5.5 | Yes |
| Fresno | 427,652 | 105 | 32,236 | 15,010 | 2.2 | Yes |
| Sacramento | 407,018 | 99 | 37,049 | 18,721 | 2.8 | Yes |
| Oakland | 399,484 | 78 | 40,055 | 21,936 | 4.0 | Yes |
| Anaheim | 328,014 | 50 | 47,122 | 18,266 | 4.3 | Yes |
| Fremont | 203,413 | 87 | 76,579 | 31,411 | 2.6 | No[1] |
| Huntington Beach | 189,594 | 32 | 64,824 | 31,964 | 6.9 | Yes |
| Ontario | 158,007 | 50 | 42,452 | 14,244 | 1.6 | Yes |
| Santa Clarita | 151,088 | 48 | 66,717 | 26,841 | 3.0 | Yes |
| Salinas | 150,724 | 19 | 43,720 | 14,495 | 4.1 | Yes |
| Santa Monica | 84,084 | 16 | 50,714 | 42,874 | 8.1 | Yes |
| Encinitas | 58,014 | 20 | 63,954 | 34,336 | 3.5 | No |
| Poway | 48,044 | 39 | 71,708 | 29,788 | 1.3 | Yes |
| San Clemete | 49,861 | 18 | 63,507 | 34,169 | 3.3 | Yes |

*Selection Criteria*

In order to present compliance costs that are representative of the widest range of California environments, a diverse selection of municipalities from the nominees is recommended. The primary factors considered are location, population, income, rainfall, and whether a stormwater drainage system (SDS) fund exists. Location is given the highest priority to ensure that the results of this survey have the widest statewide applicability. A comment from the conference call participants was to place a high priority on whether a city had a separate storm water fund. This is an indication that the city currently accounts for stormwater related expenses, allowing for further analysis of those costs. Population and income are both considered important factors, but their relative importance is unknown at this time. To make the study results more useful to other communities, it is generally sought to include both large and small cities and include cities with a variety of income parameters. Including at least one municipality with a population smaller than 100,000 will help in understanding cost for smaller cities (including NPDES Phase II municipalities). Income is a consideration as higher income communities generate a higher tax base. This may not directly relate to stormwater expenditures, but at this point it should not be ignored if it proves to be a factor. Rainfall was not a major consideration. Selecting cities by location (different geographical areas) adequately represent the range of rainfall. The range of rainfall of the candidate cities is 10 to 23 inches per year.

[1] Footnote added 1/20/05: Fremont does have a drainage fund; the original memorandum was incorrect.

*Selection Recommendations*

In considering location, the state can be divided into three sections: north, central, and south. For this exercise, the dividing lines are roughly south of San Jose and north of Santa Clarita. Each section is further distinguished between coastal and inland areas. Thus, one coastal and one inland municipality can be recommended from each section.

For Northern California, Fremont, Oakland, and Sacramento are nominated. Sacramento is the only inland city and it has a storm water fund. For coastal areas, Oakland has the advantage over Fremont because of its storm water fund. Oakland also offers a higher population density compared to Sacramento and Fremont. Based on these observations Sacramento and Oakland are recommended for the cost survey, if Oakland can overcome some timing issues regarding availability of staff time to support this project. If not Fremont could be substituted.

For Central California, Salinas and Fresno are nominated. They are ideal for location (coastal vs. inland), size (151,000 vs. 428,000), and income density (4$/ft$^2$ vs. 2$/ft$^2$). Therefore, Salinas and Fresno are recommended for the cost survey.

For Southern California, the selection is a bit more complex. San Clemente, Anaheim, Huntington Beach, Ontario, Santa Clarita, Santa Monica, Encinitas and Poway are nominated. Because smaller size communities have not been selected anywhere in California it is recommended that one of the two municipalities in Southern California be smaller (i.e. San Clemente, Santa Monica, Encinitas, or Poway). Encinitas (pop 58,000), is recommended based on their small size and upon the strong recommendation by the San Diego Regional Board. Ontario is the furthest inland, followed by Santa Clarita. The Regional Board highly recommends Ontario, and it also has a stormwater fund. Ontario's willingness to participate has not been confirmed, but their staff that was initially contacted suggested participation may not be a problem. Encinitas and Ontario are recommended for the cost survey.

Although it was not used as a criterion in the above process, income characteristics vary adequately among the recommended municipalities.

Final selection of municipalities will be made after further consultation with you and the Technical Advisory Group.

Please call me with any comments or questions at (916) 278-8109.

This appendix contains a description of the Technical Advisory Group (TAG), written TAG comments, and action items from the final meeting with the TAG. In the action items, the study team condensed all applicable TAG comments each affected section of the report. Additional notes that did not result in changes to the report are listed after the action items.

## TECHNICAL ADVISORY GROUP MEMBERS

Dr. Steven Frates is a Senior Fellow at the Rose Institute of State and Local Government at Claremont McKenna College. Dr. Frates has extensive experience in public policy analysis, with particular emphasis on local government finance. He has served as an assistant in municipal government, as the executive director of a major metropolitan taxpayer association, and on the California Constitutional Revision Commission. Dr. Frates has been a faculty member at the University of Colorado and the University of Southern California, and has lectured at other universities and colleges.

Dr. Jay Lund, is Professor of Civil and Environmental Engineering at the University of California in Davis. Dr. Lund's research involves application of systems analysis, economic, and management methods to infrastructure and public works problems. His recent work is primarily in water resources and environmental system engineering. While most of this work involves the application of economics, optimization, and simulation modeling, his interests also include more qualitative policy, planning, and management studies. His work has applied contemporary methods in cost-effectiveness and benefit-cost analysis to evaluate stormwater quality control measures, including both their costs and their likely water quality benefits. Dr. Lund is a past editor of the ASCE Journal of Water Resources Planning and Management and is a member of the International Water Academy.

Dr. Bowman Cutter is a professor of water resources management at U.C. Riverside in the Department of Environmental Sciences. His research examines cost-effective water pollution regulation, environmental federalism, and state and local environmental enforcement efforts. Current projects examine the effect of water pricing on water pollution and analyzing the cost-effectiveness of using stormwater to recharge Los Angeles area aquifers. He currently serves on the Southern California Association of Government's Water Policy Task Force.

Eugene Bromley is an environmental engineer with the Environmental Protection Agency. Mr. Bromley has 25 years experience in water quality protection. As stormwater coordinator in EPA Region 9, Mr. Bromley provides expertise to the stormwater programs in California, Arizona, Nevada, and Hawaii. In California, he participates with the California Stormwater Quality Association, giving updates on EPA policy and projects that could affect the members of CASQA.

Dan Radulescu is a senior engineer with the L.A. Regional Water Quality Control Board, MS4 stormwater permit coordinator. Mr. Radulescu has a P.E. registration in civil engineering with the state of California. Mr. Radulescu has extensive experience with stormwater implementation costs and levels of compliance. He was the primary author of a report that reviewed and analyzed stormwater budget data submitted to the Regional Board by L.A. Region permittees.

Robert Hale is a Supervising Scientist for the Alameda County Public Works, Clean Water Division. Mr. Hale is on the Board of Directors for the California Stormwater Quality Association, where he also serves as an Executive Program Committee member. He has many years of experience with stormwater programs, from his work with Alameda County and from his participation and consultation with other stormwater programs throughout the state.

Steven Sedgwick is an environmental engineer with Camp Dresser & McKee Inc. Mr. Sedgwick has more than 35 years of experience in comprehensive drainage and stormwater planning, stormwater utility evaluations, feasibility studies, pilot plant investigations, regional water resources planning, river basin planning, water and wastewater facilities design, land application and site-specific studies, value engineering and engineering assistance during construction.

# TECHNICAL ADVISORY GROUP COMMENTS

- GENERAL COMMENTS: For the 2002-3 data, I think that you did an excellent job of collecting and analyzing fragmented and somewhat non-commensurate data in order to look at the costs from two years ago. I also appreciate the depth of thought that went into your discussion of possible future costs (regardless of the shortcomings mentioned above). The nature of the available information has, I think, necessarily limited your ability to predict accurately the magnitude of costs associated with the recently added permit requirements. As a result, the report would seem to be most useful as a baseline or starting point for future cost documentation efforts. (Hale)
- GENERAL COMMENTS: First, we want to commend the research team for their outstanding job to find, if not some definitive answers, at least the right questions regarding this difficult subject of the relationship between costs and the MS4 permits implementation. It is difficult because MEP is not a clearly defined standard, MS4 permits language depend strongly on the local conditions and the willingness of the local communities to implement those requirements to protect water quality in the existing fiscal conditions. There is little guidance, if any, on this subject, and the estimates on the stormwater program implementation varies wildly depending on the initial premises for the study. Another difficult component is to determine a direct relationship between costs and water quality improvements. If we have any comments, they are triggered by the complex nature of the subject and not necessarily because of any shortcomings of the research itself. As we said, very few nationwide studies are focusing on this subject and even U.S. EPA has provided very little guidance on the subject. We also want to point out that this study focuses on the costs, and not necessarily on the benefits in water quality from the measures implemented due to MS4 permits. Therefore the reader of the study must keep in mind that there is an additional dimension of the economic equation when assessing the implications of MS4 permits costs to give a balanced view of the whole issue. (Dan)
- GENERAL COMMENTS: Due to inherent limitations, the research did not evaluate the impact in funding options, Stormwater Utility Fee vs. General Fund. Cities that rely on the General Fund to cover costs of compliance face different challenges than those with a separate, stable and dedicated funding mechanism. It is also true that municipalities funding their storm water MS4 permit costs through General Fund have a higher tendency to apply pre-existing programs, such as street sweeping, trash collection, storm

drain maintenance, etc., and their costs to the mandatory costs of compliance. In their case, it is even more difficult to discern the origin of costs in pre-existing, new, enhanced, in the absence of clear guidelines. In extreme instances, in some cases of municipalities depending on General Fund and pre-existing programs, contingent on how the requirements of the permit and costs are interpreted, the cost of compliance can vary from low hundreds of thousand dollars to a high dozen million dollars (!) per year for the same small municipality. A number of municipalities even pointed out this discrepancy, based on different interpretations, in their annual reports. This lack of guidance also fuels the debate of the correct impact of MS4 permit compliance costs that can vary from single to hundreds of dollars(!) per household per year. Obviously there is a significant difference from manageable to exorbitant costs. Unless there are clear guidelines and transparency on how to determine the correct compliance costs with MS4 permit requirements we will face this debate from reasonable to exorbitant for years to come.

- WATER QUALITY (Sect. 3) Review major water quality problems that SW Program addresses for each city (Lund)
- IDENTIFYING TRUE COSTS: Establish a 1990 costs baseline and then determine what are the true additional costs due to the stormwater regulations by comparing the 1990 baseline with the data investigated (2002-03). One example is to use per capita costs: if in 1990, the city was spending $10/y/capita for street sweeping, in 2002 the cost (in dollars adjusted for inflation) would be (e.g.)$14/y/capita. Then determine the portion attributable to the SWMP implementation and MS4 permit compliance. Only this type of transparent analysis will reveal the true additional costs, new financial burden, mandated by the existing MS4 permits. This type of analysis may add new findings to the one identified presently in the study. This approach should be used for street sweeping, catch basins and storm drain system, trash collection, hazardous waste recycling programs, flood control component of the city's overall stormwater management, etc...

  How these facts impact the conclusion of the research?

  These types of observations are very important since they reveal the significant importance of such expenditures, such as street sweeping, in the make up of the attributed costs for compliance with the MS4 permits.

  This is even more necessary for cities that depend solely on General Fund money to comply with the MS4 permit requirements. Many pre-existing, well-established programs, in some cities, count now as "exorbitant" MS4 permit costs compliance, when the only change was to move the expense from one column into another in the cities financial reports. (Dan)
- COST/DATA REPORTING: We suggest that a better option for reporting is to use GASB or similar standardized approaches to costs and infrastructure inventory may be a better way to assure transparency. The ways suggested by the research to report cost data seem reasonable, but if this effort can be tied to an existing standardized approach, such as GASB, that may be very valuable since it will provide for consistency statewide and even nationwide. It may be that GASB does not cover all reporting categories. The reporting may use a hybrid between the existing GASB itemization and the approach suggested by the research. An additional approach maybe to lobby the GAS Board to make changes in the accounting rules to allow for water quality itemization. (Dan)

- COST ALLOCATION BY CATEGORY: I would replace the regressions with the interesting analyses contained in appendix G as a starting point. First look at how much the variation in the cost of each program component contributes to the overall cost variation. It appears that the variation in the Municipal category is the biggest driver. However, what I am not sure is whether that is because categories are not consistent across cities and different cities place different costs in the municipal category. Please comment on that possibility. It looks like the variation in overall management is the second biggest driver of the overall cost variation. Again, please comment on whether this is due to "true" cost differences or category-confusion. A very rough statistical methodology to tease this out is to find out the correlation coefficients between each of these two categories and each of the other categories. If you find some strong negative correlations, this is an indicator that really the cost differences are just due to category confusion. In the end this may be a topic that calls for a more qualitative answer. I would like to see a discussion of, taking into account what you know about data quality, whether you think the high cost/household cities tend to have higher costs across the board, or whether their higher costs are generally due to having higher costs in one category or another. From the data, the latter appears to be true, but I don't have a sense of the data quality and how the categories are affected by cost-shifting. (Cutter)
- BUDGET/COST ALLOCATION: (table 6.2) Can percentages of cost assignment add up to 100% to show how the total budget is allocated? (Lund)
- INDUSTRIAL PROGRAM COST PER INSPECTION AND SITE, AND THE EQUIVALENT NUMBERS FOR THE CONSTRUCTION PROGRAM COSTS: Both these programs have almost order of magnitude differences in costs. Please write up the reasons for these differences more thoroughly. I suspect that some of the reason for these large cost differences is cost-category confusion. You should indicate whether you think that is the case, and then indicate which citie(s)' normalized inspection costs you judge to be most satisfactory and why. I know this is going out on a limb, but few observations call for a more qualitative analysis. The large cost ranges diminishes the amount of information in the report and an indication of where the cost numbers likely lie for your best data cases would add quite a bit. (Cutter)
- STREET SWEEPING COSTS: Another possible angle to examine the overall cost range is to break out street-sweeping vs. non-street-sweeping expenditures, since street sweeping seems to be the largest element of the biggest category, and see what the cost/household ranges are in this breakdown. Then you could comment on whether street-sweeping costs are the big driver behind cost differences. Further, you could remark on whether it appears that some communities are doing more street-sweeping than necessary to comply with their permit (do we have a curb miles swept and total curb miles for each city?).(Cutter)
- STREET SWEEPING COSTS: (Table 9.3) Explain street sweeping unit and $cost/curb mile swept variability, in particular the low/high values. (Lund)
- STREET SWEEPING COSTS: On page 52, the paragraph just above the Table 9-5, states: "cost savings can be realized if cities are allowed to focus on the most cost effective programs rather the following overly prescriptive permit requirements." For example, since street sweeping is the most significant share of the stormwater costs maybe it

should be determined if this program is also cost effective the way it is performed presently. This is one avenue to improve the cost-effectiveness relationship. Why spend a significant amount of money if the impact may be insignificant? Some studies in the literature suggest that fact. Secondly, the permits are "overly prescriptive" in many instances due to Permittees specific request to the Regional Board for clarification and guidance in the permits on what they are required to accomplish, when and how. (Dan)

- WATERSHED MANAGEMENT COSTS (Sect. 8 ,Pg. 44) Elaborate on watershed management cost (Lund)
- TMDL COSTS: We strongly recommend the inclusion of TMDL portion of the report in a separate attachment or appendix. The TMDLs cost review were not part of this proposal. The costs vary in a wide range, based on various assumptions and scenarios, none of the cities are currently implementing TMDLs via a MS4 permit. We believe that the inclusion of TMDL discussion in the body of the main report will confuse things. The job of accurately estimating TMDLs implementation costs is complex and open to many interpretations. It is opportune to present various ranges and costs under the research done up to date but we are a long way to agreeing on one set of values. Therefore we believe that the TMDL research on future costs should be included in an Appendix to the report. (Dan)
- TMDL COSTS: p.55 section headed Adding future costs...This is pretty unclear, either expand it or drop it. I think you mean to say something like if current cost estimates are X, and TMDL estimated costs are Y, total costs should be something less than X+Y since current and TMDL expenditures overlap. But I am not quite sure that is what you mean. (Cutter)
- LAND ACQUISITION COSTS: The Advanced Treatment (Gordon, et al.) discussion mentions that land costs were included in that $37 billion cost estimate. However, Section 9 draws in part from Appendix H. Most of the discussions of treatment system examples in the Appendix do not make it clear whether land acquisition costs were included in the cost figures given. In my view, this omission tends to weaken the credibility of the figures used. In the case of the Tule Ponds (the one with which I am most familiar) the $360,000 cost figure does not include any consideration of land costs. The site was, and is owned by the Flood Control District so no purchase price is included. The Authors do touch on the subject when they mention in some examples how land necessary for other purposes (e.g., parking lots) can be put to dual use for stormwater treatment (which makes land acquisition unnecessary). However, the dollar figures given for the various systems need to include mention of whether land costs were included and what they might be if the were not. This is especially true (as you point out) in densely populated urban areas. In the Tule Ponds case, if land were to be purchased on the open market in the center of Fremont, the total cost of the project would be an order of magnitude higher. On the issue of land costs being lower in less densely populated areas (a point that the report makes). In the San Francisco Bay Area, the need for treatment is greatest in densely urbanized areas and almost non-existent in rural areas. In our area, population density tends to increase as one moves toward the Bay. Since stormwater can't really be pumped uphill to treatment facilities, our need for such facilities tends to

be greatest exactly where land prices are highest. This limits our flexibility in locating treatment facilities based on land costs. (Hale)

- DUAL BENEFITS: It is not clear how to account for dual benefit activities. In the case of city of Sacramento, pump station cleaning may be attributable also to maintaining the hydraulic integrity of the system, a water quantity, flood control issue, not necessarily due to water quality concerns. (Dan)
- DATA ANALYSIS: More can be done on the attempts to define what factors lead to higher or lower costs for total costs as well as element by element. The first step is to relegate the various regression analyses to appendices or to drop them altogether. Seven observations are not sufficient for a statistical analysis. This is evidenced by the confidence intervals in Figure 1, which appear to be below zero for three cities. However, there is even less information in this regression than it first appears. Comparing aggregate stormwater spending to aggregate household income is somewhat misleading because they are both driven simply by the overall size of the city. A better regression would be per-household stormwater spending on household mean or median income. I suspect the R2 would be quite a bit less and the confidence intervals correspondingly greater. My recommendation is to simply drop the regressions from the body of the report. (Cutter)
- DATA ANALYSIS: (Section 9.1) Analysis seems simplistic. Should cost be related to the problem, which might be proportional to population or level of economic activity? Cost/ HH values need to be further explained. (Lund)
- DATA ANALYSIS: p.52 2nd par. Sentence beginning with: The present worth cost... please explain this sentence further, why is there such a large cost range? Explain to the reader why the cost-per-acre and cost-per-volume estimated difference and the range in the land prices. You can do this in a footnote. (Cutter)
- DATA ANALYSIS: Explain rainfall as the best indicator for cost (Lund)
- VARIABILITY IN COSTS AMONG CITIES: I would like a final summing up in the report of why the overall cost/household range is large. Again, this will probably have to be more qualitative, but I think that is fine. I would like the reader to come away with a sense of why one city has costs almost three times larger on a per-household basis. That qualitative analysis should think through the following questions: 1) even within the category of cities with good stormwater programs are some cities doing a lot more activities than others?; 2) If so, is the extra activity necessitated by say, greater amounts of construction or other factors? Are some cities in the midst of infrastructure activities so that you would expect say a three year average of stormwater costs to be in a much closer range? Perhaps you will conclude that the cost differences are really inexplicable given what you know. If so, that in itself is interesting and you should suggest further avenues for research into hypotheses suggested by your experience in this project and explain why this research does not give insight into the reasons behind the large cost range. (Cutter)

# TAG MEETING NOTES FROM DECEMBER 14, 2004:

**Action Items**

1. Clarify that, beyond the objectives identified in the report and contract, this report also serves as a step toward establishing cost numbers to be used in budgeting and cost/benefit evaluations. Note that this report does not address the benefits of those permit required stormwater activities that are assumed to improve water quality. Note that the reports use as a budgeting tool may only be timely for Phase II permittees. **Location of Change: pg ES-1, Section "Task A"; Section 1, section "Task A"**

2. Double check consistency of classifying costs (e.g. existing, enhanced, new). Add discussion defining these terms and discuss the likelihood that enhanced cost is, for the most part, pre-existing. Display graphically. Note any differences between the accounting practices of cities with a SW utility fee and those without, especially regarding the amount of the costs that are 'existing' or 'enhanced'. If apparent from the study, discuss the relative importance of having a fee versus having a designated fund, without a fee to fund it. **Location of Change: Figure 9.4 and Section 2.5 and additions to Section 9.1, p49.**

3. Replace the regressions in report with qualitative discussion on cost differences between cities. List major water quality control strategies and affected water bodies for each city. This may help explain some cost variation. Explain differences in cost between cities qualitatively. (e.g. Fresno low because joint use facilities, permeable soils, available land). Note any large infrastructure campaigns of the cities. Move regressions to appendix with the note that we tried various correlations but a model was not successfully developed, partly due to the small sample size. Only do regressions on normalized cost, not aggregate costs, which are only a surrogate for city size. Include a note in the body of the report that the failure of the regressions was expected due to small sample size and that the regressions are presented in an appendix as anecdotal information.
   **Location of Change: Discussion additions and modifications to Section 9.1, Deleted regression figures in ES and section 9.**

4. Move TMDL and future cost discussion from Section 9 to an appendix. Add a note to the appendix and executive summary that Task B research was done assuming the MS4 permitting process as it stands presently, using an iterative process of enhancing implementation of BMPs. This scenario may overlap with TMDL process, but it is not necessarily the same. TMDLs may be folded in MS4 permit as allocations, as appropriate, depending on the impairments to receiving waters. Note that the costs for LA may be specific for LA only and are difficult to extend to other areas with

different characteristics. **Location of Change: Note added to Introduction and modified discussion moved to appendix G**

5. Downplay comparisons between TMDL costs, which are future costs that are variously estimated, and MS4 permit compliance costs incurred by the cities surveyed costs. TMDL cost estimates are total costs and not the cost to the cities exclusively. Similarly, note that Gordon costs are city-only costs. Take Gordon costs out of table in Executive Summary and discuss in the text.
   **Location of Change: Section 9 future cost discussion, including TMDLs, modified and moved to Appendix G. Gordon costs taken from ES table and moved to text**

6. Add TAG comment section in Section 10 on cost tracking benefits. Propose that if the permittees have a correct cost accounting/reporting system, they would be granted an additional quantity of points towards their receipt of a grant under a state/federal program; for example, Section 319(h) grants are evaluated on a point ranking system that is established by a state. If the cost accounting/reporting information were tabulated pursuant to the state's suggested format, that applicant would receive a bonus allotment equal to a boost in total points of approximately 15 percent. This would alert that permittee to the benefit in competing for these grants as a pre-requisite to establishing the appropriate cost accounting system. The proposed system would benefit from review and acceptance by the California League of Cities. Note the process in developing consistent cost reporting in the region and the associated benefit to the city with developing and justifying stormwater utility fees. Note that our recommendations for cost reporting are only the first step in this process of developing consistent cost reporting. This process includes notifying cities of reporting goals, identifying whether costs are minor and local and applicable to other cities, review reported costs for quality and consistency, and provide feedback to the cities. Identify appropriate categories with definitions to allow clarification between differences; with appropriate definitions, the individual entities could probably better assist the permittees to understand the benefit of reporting costs in a correct fashion. For example, a reported cost item may be illegal discharge elimination and would have clarified definitions to differentiate between end-of-pipe actions, in-pipe actions, source identification, and source detection. **Location of Change: Discussion added to Section 10.2 and 10.3, pages 51 and 56. Regressions moved to Appendix G.**

7. Make sure legal fees are properly discussed. Appellant fees are excluded, but legal advice on program implementation and response to citizen suits are included. We assume that if legal fees are incurred, it is part of the cost of doing business. This is not an assumption that all lawsuits are frivolous and therefore attorney fees are justified expenses. Neither is it an assumption that all legal advice is to challenge the lawsuit rather than to acquiesce to the demands of the lawsuit. **Location of Change: See discussion in section 9.5**

8. Append all written TAG comments to the report. **Location of Change: See Appendix J.**

9. Report cost without existing and enhanced 'big-ticket' items such as street sweeping trash collection, storm drain maintenance, drain line cleaning, channel cleaning, and pump station cleaning, recycling, hazardous waste roundups, etc. Note that an unknown portion of an "enhanced" cost is appropriate to count toward the additional financial burden of permit compliance. Also, include a suggestion that a three years average, 1987-1990, may be used as a baseline cost to figure out "enhancement" portion costs based on the post 1990 MS4 permit requirements and caveat that unit cost for sweeping varies. Note that sweeping is an enhanced cost and the majority of effort pre-existed the first stormwater permits. Also caveat that all programs may still have hidden costs that could not be identified by the cities. An example is backup equipment for street sweeping, but note that these costs are also preexisting. **Location of Change: See section 9.4 for added discussion of existing and enhanced costs and see Section 2.5 for discussion of using baseline costs.**

10. Consider using pie charts for each city to show distribution of costs among categories. **Location of Change: See individual city sections (sections 3-8)**

11. Note that Post Construction costs are expected to increase as cities move into full implementation of SUSMP type requirements for new development and redevelopment. Note that the reported costs are particularly misleading for cost projection purposes since the research coincides with the start of SUSMP type requirements implementation. **Location of Change: Section 9.5, Qualitative Discussion of Stormwater Costs for Selected Cost Categories.**

**Additional meeting notes**

1. Cities may try to push as much general fund expenses as possible to stormwater a fee, but public response to fees helps balance cost. [I believed we discussed that cities successful in passing a SW fee were very transparent in the process, limited in scope, and going to great lengths to tie the SW fee to activities and capital investments related directly to water quality enhancements and benefits. Probably is not a bad idea to put some positive "lessons learned" from those successful cases in passing a SW fee.] (Dan)
2. GASB 34 may not be a realistic method to encourage cost reporting, especially on the short term. [is there a way to move this idea at a national level? That GASB can develop some standards for such a purpose, or add to an existing one?] (Dan).
3. Hamilton County, Ohio costs were not captured till 2001, for Phase II non-Cincinnati areas. Took two years to establish more consistent cost reporting. The cost had been

accounted for from 2001 through 2003 for Phase II cities, but that even these costs were "too vague" to allow appropriate interpretation by all 44 permittees. When CDM conducted the next evaluation required to establish a charge for these functional activities, CDM had to more precisely define the activities and quantify the level of effort for each action (Steve).

4. Wisconsin and Florida: cities are given points for having a fee, points awarded if utility charges are above $3.50 (80), below (40), and none (0). Points are a criterion for grant applications. Expand the last sentence to read "This approach would assure that permittees competing for grants would receive between 15 and 20 percent bonus points in the priority ranking system utilized by these states to award grants" (Steve).
5. Average cost per billing unit is $2.92/month for all stormwater including flood. Only for cities with stormwater fund/fee. Insert "Based upon evaluations conducted for stormwater utilities charging a stormwater user fee as of December 31, 2003, the total monthly charge per residential dwelling unit was $2.92/month. The services provided for this fee included all components that a given jurisdiction was incorporating into the stormwater management program, but could have been augmented/supplemented with additional monies from other sources that weren't clear in the writer's review. However, greater than 75 percent of those systems reviewed included some costs for quantity management in this fee." (Steve). [See my comment at first point, it seems that a focused SW quality fee will be on average much less that $3/month/billing unit. city of LA with its current $18/yr/household seems to be right there, at the average.] (Dan)

# FRBSF ECONOMIC LETTER

Number 2004-27, October 1, 2004

# House Prices and Fundamental Value

The performance of the residential housing market over the last ten years has been remarkable. According to the Office of Federal Housing Enterprise Oversight (OFHEO), house prices have appreciated at an annual rate of 5.4% on average (68.9% over the whole time period). Perhaps even more remarkable is that the performance was strong even when economic activity overall was weak. Average annual appreciation rates have been 7.4% (26% in total) since the collapse of the Nasdaq in 2000 and 7.1% (20% in total) since 2001:Q1, the beginning of the 2001 recession. In contrast, since the start of the 2001 recession, the S&P 500 and Nasdaq have averaged negative annual returns of −2.43% and −1.42% respectively.

These kinds of statistics have generated an enormous amount of commentary along with suspicions of a house price bubble. At first glance, housing would appear to be just the type of market that is susceptible to systematic mispricings. Most market participants have little experience, making transactions only infrequently. Asymmetric or incomplete information between buyers and sellers about demand and prices is acute. Even with the advent of new technologies, the matching of buyers with sellers remains cumbersome and slow. And unlike other markets, there are no good ways to "short" the housing market if prices get too high.

This *Economic Letter* describes one of the measures commonly used to gauge the fundamental value of housing—the price-rent ratio. We describe the kinds of forces that cause the ratio to move over time and document which forces appear to be most important. We document the way that the housing market typically adjusts to changes in economic fundamentals.

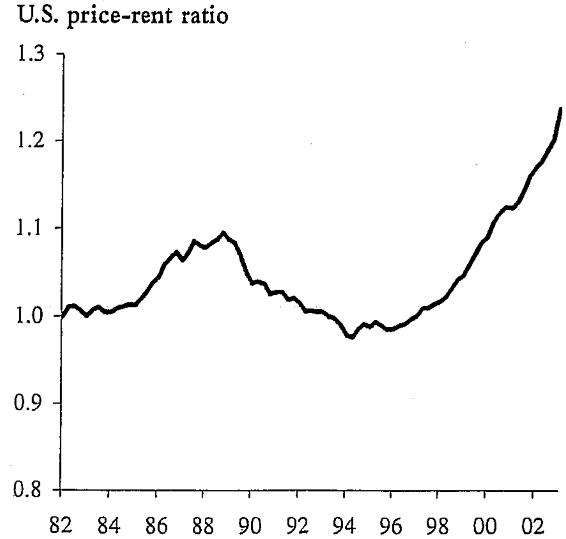
**Fundamental value and the price-rent ratio**

The price of housing is determined by the forces of supply and demand for the housing good. So, naturally, many economists try to relate prices to variables that might shift supply and demand, like interest rates and household income. Price dynamics are often described in terms of the interactions between these variables and the natural constraints on delivering new supply to the market (see McCarthy and Peach 2004).

We borrow from the finance literature to take a different approach. The finance paradigm holds that an asset has a fundamental value that equals the sum of its future payoffs, each discounted back to the present by investors using rates that reflect their preferences. For stocks, the payoffs requiring discounting are the expected dividends. This approach can extend to housing by recognizing that a house yields a dividend in the form of the roof over the head of the occupant. The fundamental value of a house is the present value of the future housing service flows that it provides to the marginal buyer. In a well-functioning market, the value of the housing service flow should be approximated by the rental value of the house.

A *bubble* occurs—in either the stock market or the housing market—when the current price of an asset deviates from its fundamental value. Right away we see that bubbles are difficult to detect because fundamental value is fundamentally unobservable. No one knows for sure what future dividends are going to be, or what discount rates investors will require on assets. Despite this obstacle, analysts still find it helpful to construct measures of fundamental value for comparison to actual valuations. One popular measure is the price-dividend ratio, which corresponds to a price-rent ratio for houses. The price-rent ratio for the U.S. housing market is in Figure 1. The price series is the existing home sales price index published by OFHEO; this index is a repeat sales index, meaning that index changes are compiled from the price changes on individual houses that turn over during

**Figure 1**
**U.S. price-rent ratio**




Sources: OFHEO and BLS.

the sample period. One of its drawbacks is that it does not fully differentiate between pure house price appreciation and price changes due to depreciation or home improvement. The rent series is the owner's equivalent rent index published by the Bureau of Labor Statistics (BLS); this series is intended to measure changes in the service flow value of owner-occupied housing. The figure suggests that current prices are high relative to rents. More precisely, house prices have been growing faster than implied rental values for quite some time: currently, the value of the U.S. price-rent ratio is 18% higher than its long-run average.

It is tempting to identify a bubble as a large and long-lasting deviation in the price-rent ratio from its average value, just like the one that we see in Figure 1. But exactly how large and how long-lasting a deviation must be to resemble a bubble is far from obvious. There is no reason to believe that a price-dividend ratio should be constant over time, even in the absence of bubbles; in particular, Campbell and Shiller (1988) showed that the value of the ratio today can increase only if there are expected future increases in dividends, expected future decreases in returns, or both. This simple model of the price-dividend ratio is based on a simple identity and the definition of a return as the sum of a dividend yield and a capital gain/loss.

To make the implications of this simple model more concrete for our housing application, imagine a real estate market near a military base that has just been scheduled to close five years from now. The inevitable job loss associated with the closure is an adverse shock to the demand for housing. This should cause a decrease in the future value of the housing dividends on houses in the area, driving house prices down immediately. Current rental contracts, however, should be relatively unaffected because the closure is so far off in the future. Thus, the price-rent ratio should decline. Alternatively, suppose the government could credibly promise to reduce taxes on real estate and keep them low forever. This change would probably lead to a higher demand for housing; at the margin, households would have the incentive to shift savings from financial assets to housing. In addition, the elimination of uncertainty about future tax rates would imply that houses are safer assets, requiring lower future returns. In this case, the price-rent ratio should increase.

**What moves the price-rent ratio?**

Given a notion of the sources of variability in the price-rent ratio, it is natural to wonder which sources are most important. Cochrane (1991) conducts this exercise for the case of stocks and finds that most of the most variation comes from changes in returns.

We conduct Cochrane's experiment for houses. To construct the price-rent ratios we use OFHEO's existing home sales index and the owner's equivalent rent index published by the BLS. We use quarterly data, ranging from 1982:Q4 to 2003:Q1. The constraint on the sample period is that the owner's equivalent rent series does not begin until 1982. We could extend the rental series back further by using a pure rent series, but only at the cost of severing the link between an owner-occupied price in the numerator of our ratio and an approximation to an owner-occupied service flow value in the denominator.

The basic insight of the empirical research on price-dividend ratios is that movements in the price-dividend ratio can be decomposed into two parts: movements relative to future expected dividend growth rates, and movements relative to future expected returns. In theory, these future variables are unknown to the investors when they set prices. In this application, we set the expected future dividend growth rates and returns equal to the actual values that occurred. Also in theory, we should assume all "future" dividend growth rates and returns to mean those extended to infinity. Obviously, this is not possible, so we study how the price-rent ratio moves relative to the next 15 quarters of rental growth rates and returns. (We experimented with other horizons, and found that the results did not change much.) Note also that we are unable to incorporate the current episode of price appreciation. We run out of observations before we can say anything definitive about the recent house price appreciation.

The main result from this decomposition is that the behavior of the price-rent ratio for housing mirrors that of the price-dividend ratio for stocks. The majority of the movement of the price-rent ratio comes from future returns, not rental growth rates. This will not comfort everyone, as it implies that price-rent ratios change because prices are expected to change in the future, and seemingly out of proportion to changes in rental values. A more comforting conclusion, however, is that, despite the well-known frictions in real estate markets, the dynamics of a common valuation measure are still similar to those observed in a near-frictionless market like the stock market. It may appear that returns are quite volatile relative to changes in rental values, but this is true for stock prices as well and only serves to underscore our inability to understand how expectations and required rates of return on assets are formed.

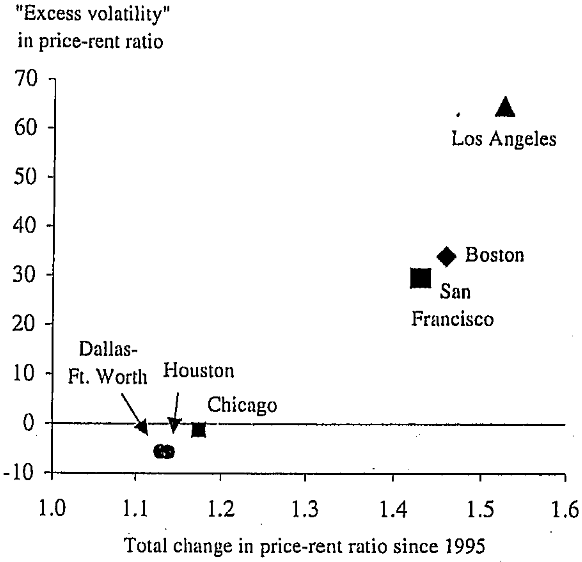
Another result is that almost all of the movement in the aggregate U.S. price-rent ratio was accounted for by two factors—the proxy for future growth in rents and the proxy for future returns. Put another way, other factors, such as bubbles, do not appear to be empirically important for explaining the behavior of the aggregate price-rent ratio. At the same time, when applied to local real estate markets, in many cases the movement in the price-rent ratio predicted by the model is much greater than the actual movement; specifically, the results indicate that something other than our measures of future rent growth and returns explains price-rent ratios. While we do not know what this "something other" is, the more common overstatement of volatility is caused by a much stronger comovement between the price-rent ratio and future returns than the comovement between price-rent and future rent growth.

The excess of the price-rent ratio volatility (the difference between the movement predicted by the model and the actual movement) can be traced to the volatility of house prices in local markets. Most recently, local housing markets that historically have had "excess" volatility in future returns also exhibit high house prices compared to fundamentals. This is shown in Figure 2, where the vertical axis measures the excess volatility in percent terms; zero corresponds to the case in which the model and our implementation explain the actual price-rent ratio precisely. The horizontal axis measures the price-rent ratios normalized to have the value of one in 1995:Q4.

The figure shows that in some markets, such as Dallas and Chicago, the combination of future growth in rents and future returns account for most of the variation in the price-rent ratio. Price-rent ratios in these markets appear to behave as do those in the national market. Other markets, such as Boston, Los Angeles, and San Francisco, have return streams that are much more variable than the price-rent ratios they are supposed to be tied to. Perhaps not coincidentally, these markets are thought to be ones where the supply constraint on new construction is particularly tight. Also, these are markets that now appear to be most highly valued.

**Conclusion**
The price-rent ratio for the U.S. and many regional markets is now much higher than its historical average value. We used a model from the finance literature to describe how the price-rent ratio can move over time. We found that most of the variance in the price-rent ratio is due to changes in future returns and not to changes in rents. This is relevant because it suggests the likely future path of the ratio. If the ratio is to return to its average level, it will probably do so through slower house price appreciation.

**Figure 2**
**Regional differences in price-rent ratio**




**John Krainer**
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# Creating Affordable Housing

Despite statistics and economic realities that can seem dauntin
those seeking a home of their own that is safe, decent, and affo
municipalities working together can make affordable housing a

### Related Showrooms

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- **Simplex** - Modular Construction for Homes, Apartments and
- **Foreclosure.com** - Foreclosed Properties in Your Area

Since WWII the federal government has had its hand in promoting and supporting affordable housing through GI Bills and low-interest financing. These policies and subsidies were very effective in helping returning GIs and other first-time homebuyers get into their first homes. But with rapid economic growth and the Baby Boom, traditional federal subsidies alone have not been able to keep up with the growing affordability gap. Families need safe and decent places to live. Communities need an adequate supply of housing, at all price levels, and businesses need housing that is affordable for their workforce.

Affordabl
homes for
our comm
Druley nei
Massachus

### Affordable to Buy

The Federal Government defines housing
affordability as housing costs that do not exceed 30 percent of
Housing Costs are defined as rent or principle, interest, taxes &
(PITI). If we assume you're making the 2002 median income o
you would be spending no more than $1083 per month on hous
assume that you are purchasing a home at the 2002 median pri
Association of Realtors), you would need to come up with a do
purchase that home and still meet the definition of "affordable"
factors that influence this deal including mortgage rate, term (l
and closing costs. Change any of these factors and your down p
payments could go up or down. And when you factor in points
total cash outlay at closing would be over $33,000! By the gov

A005114

home may be affordable to own, but with this much up front ca affordable for you to purchase?

**Affordable to Build**

One major factor in affordability is the cost to produce housing claim—and government statistics support these claims—that h leads the nation out of recession. It's no wonder when you cons benefits not only the trades but also manufacturing, profession transportation. But the demand for new housing can cause shor materials. Delays due to weather or permit issues also add to cc passed on to the buyer. Builders of new homes typically operat profit margins of five to ten percent, so even a small spike in cc a builder's profit and increase housing costs to buyers.

An experienced builder can help the homebuyer keeps costs do and material selection. This process is called "value-engineerin your best interest to find a builder who thoroughly understands industry certainly benefits from innovations in materials and m builder is generally not able to have much of an impact on over Think of it this way: A $750,000 mansion, at its core, is built w materials as a $125,000, three-bedroom ranch. It's not just the f inflated price tag.

**Bringing Housing Costs Down**

One of the key ways to achieve affordability is to increase hous regulations at the federal, state, and local levels can have a tren affordability. Wetlands regulations, for example, take large trac housing market, reducing supply. Local zoning rules that requi single-family home also add pressure to land supply. There are developing any parcel of land including site planning and perm and water. All of these costs have to be included in the selling built on the parcel. If zoning or other regulations limit the parc one house, all of those development costs will have to be borne making the price go higher. If zoning regulations allow a highe more houses per parcel—the builder can spread the land develc housing units, so the same house would actually cost less to bu

**Housing Policy for Affordability**

Local governments usually jump in when a shortage of afforda the vitality of the community. In many areas of the country, es police, firefighters, medical workers, and teachers cannot affor communities where they work. Some municipalities are now o incentives to close the affordability gap and lure workers close measures employed by local and state governments include ho mandates and inclusionary zoning ordinances.

In Massachusetts, for example, Act 40B is a state statute that re in the state to have a housing policy with the goal of having at housing stock affordable to people earning 80 percent or less o (AMI). Such measures may require that developers increase ho efficiently use available land. Some rules require developers to of the homes they build affordable. Act 40B was one of the firs country and has been partially responsible for the creation of a of housing that meet this level of affordability. Maine followed

Today there is a growing list of states, in every area of the cour pending legislation that promotes and/or mandates housing affc

There are also a number of non-profit organizations and progr address housing affordability. Community Land Trusts (CLTs) private, non-profit entities that secure grants and donations to p for long-term affordability. Most CLTs sell the houses but hold through long-term land leases to the house owner. Most CLT le equity limitation so that when the house is sold, it will remain a buyer. Other organizations include Habitat for Humanity, Neig Finance Agencies, and Local Housing Authorities. One relative administered through Local Housing Authorities, allows eligibl Section 8 housing vouchers to purchase a home. Local banks ar have the latest information on loan programs for first-time buy

Text by Tom Peterson




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# The Challenge of Housing Affordability

Pillsbury Winthrop Shaw Pittman

By *Lewis G. Feldman* and *Douglas A. Praw* of Pillsbury Winthrop Shaw Pittman LLP

Every cloud has its silver lining -- and every silver lining has its cloud. The wisdom of the first statement is evident in the positive impact that the collapse of the securities markets in 2000 had on interest rates and residential real estate prices over the past few years as investors shifted out of stocks and into real property assets, like homes, which saw a tremendous increase in value. The cloud in the silver lining of higher real estate prices, however, is that affordable housing, both rental and single family, is fast becoming an oxymoron. As home prices continue to rise, more and more Americans find themselves priced out of home-ownership and struggle to find affordable rental housing. Affordable housing is crucial in attracting and retaining business, sustaining employment growth and ensuring a healthy political and economic climate in our communities. Recognizing the impact that affordable housing has on our communities, Congress and local government have stepped in with initiatives that promote and facilitate the construction of affordable housing.

## Seller's Market Strains Rental Housing

One place where a seller's market exists is in Southern California's residential real estate sector, where supply is dwarfed by demand. Since 1984, over 287,000 net jobs were created in Los Angeles and Orange Counties, yet only 78,000 single family residences were built. According to DataQuick, the median price of an existing home in California in November 2003 increased 17.8% year-over-year and sales increased 15.7% over the same period. The median home price in Los Angeles is now in excess of $365,000, which, at today's interest rates, requires a monthly debt service payment of around $1,750, assuming 20% down and a 6% interest rate. Meanwhile, median monthly income in Los Angeles County for a family of four is $3,640.

Since an affordable home is commonly thought of as one that requires the payment of no more than 30% of a family's annual income toward principal, interest, property taxes and insurance, a quick calculation between income and housing costs shows a dramatically widening gap between what we earn and what we can afford to pay for a home. Staggeringly, one in eight lower-income working families earning at least the full-time equivalent of the minimum wage reported spending more than half of their incomes on housing.

However, statistics alone do not adequately convey the impact of a lack of adequate affordable housing on a community. A decent, affordable place to live brings with it certain quality of life benefits fundamental to a strong and stable nation. Improvements in housing can be linked to improvements in schools, safety, job access and transportation.

Some incorrectly believe that higher housing costs singularly affect low-income families. But the reality is that moderate-income families - including teachers, safety personnel, hospital workers and senior citizens - must stretch to make ends meet, let alone afford to own a home. These homeowners often have limited savings and increasingly must rely on adjustable rate loans to afford their initial purchase. A job layoff, a salary freeze or a decrease in retirement benefits could easily result in a mortgage default. This economic pressure is hardly conducive to ensuring a quality of life for the average citizen and makes it increasingly difficult for communities to attract the best and the brightest.

As middle-income families are pushed out of homeownership by increasing costs, rental housing is similarly strained by the increased demand. This translates into higher rental rates, which has a domino effect on lower-income families.

The root causes for the lack of affordable rental housing include the rising housing production costs in relation to family incomes, inadequate public subsidies, restrictive zoning practices, adoption of local regulations that discourage housing development, implementation of prevailing wage legislation and loss of units from the supply of federally subsidized housing. Low interest rates and wealth earned in the stock market bubble also helped to drive up home prices. Further, as a reaction against long commutes and large subdivisions, homebuyers and renters rediscovered older, more traditional neighborhoods. This rediscovery caused prices in these previously affordable neighborhoods to increase. Irrespective of the cause, the demand for convenient, affordable housing is not being met.

**asing the Strain**

Despite the bleak outlook, there are initiatives that can be utilized by the private sector to keep a project's bottom line in the black while also bolstering the supply of both affordable rental and single family housing. Congress, re-cognizing that the problem of affordability now affects one-quarter of the nation, has implemented incentives to produce new affordable rental housing. The Low Income Housing Tax Credit ("LIHTC") has provided investors with a ten-year stream of credits against income in exchange for producing affordable rental units. Each state is allocated a share of the LIHTC based on its population and is charged with allocating the LIHTC among qualified developers.

In California, for example, the demand for credits usually exceeds their availability by about four-to-one. The California State Treasurer's Office established the Tax Credit Allocation Committee ("TCAC") in order to mete out tax credits. By federal mandate, TCAC adopted the Qualified Allocation Plan, which further refines the selection process for tax credit allocation, giving preference to those developments that encourage smart growth, implement energy efficiency and serve the lowest-income tenants. Preference is also given to those developments where the affordability restrictions will remain in place for the longest period of time.

In New York, tax credits are awarded by the New York State Housing Finance Agency. This state agency has its own Qualified Allocation Plan to allocate tax credits among developers that similarly includes a scoring system that evaluates projects based on location, housing characteristics and the intent to serve a population of individuals with children.

ıvvy developers will gear their projects and their LIHTC applications to ensure a tax credit allocation. As ıuch as 100% of a development's construction costs can be financed through a combination of tax credits and conventional or bond financing.

To combat the strain of increasing home prices on homeownership, the newly proposed Homeownership Tax

Credit program ("HTC") (which is modeled on the LIHTC program) would allow single family developers of affordable housing to sell tax credits against income for constructing or rehabilitating homes that meet affordable program requirements. If adopted, the HTC legislation is expected to provide $2 billion in new private investment in affordable housing per year. The program targets census tracts with median incomes of 80% or less of the greater of the area median income or state median income. Each state would receive an annual allocation of tax credits starting at $1.75 per capita, subject to a cost-of-living adjustment. For-profit and community-based developers would then receive an allocation of the credits under a competitive process, guided by each state's annual plans for affordable housing. Developers can then sell the tax credits to corporate investors and use the sale proceeds to fund the gap between the cost of development and the price at which the home can be sold to an eligible buyer.

On the local level, municipalities are passing inclusionary zoning ordinances that require developers to include a number of affordable units in new apartment complexes or new developments. In exchange for these set-asides, a developer is eligible to receive land use and planning concessions to offset the cost of the affordable units. These concessions are available to any developer building in the area restricted by the inclusionary zoning ordinance.

Tax-exempt bond financing can also help a multifamily developer tighten the gap between project costs and housing affordability for its tenants. The interest rates on the bonds offered by local government issuers is significantly below the rates offered through conventional institutional financing, even with today's low interest rates. By teaming up with an eligible issuer, a public-private partnership can be formed that will provide the developer with the extra funding needed for an affordable housing rental project.

Another option to developers interested in promoting affordable housing is not so much a financing mechanism, but a land use planning alternative called "smart growth." The smart growth concept centers on policies designed to counteract urban sprawl. These policies include limiting outward expansion, encouraging higher density developments, encouraging mixed-use zoning, reducing travel by private vehicles, revitalizing older areas and preserving open space. While affordable housing is not a direct goal of smart growth, it can be a direct result of the smart growth initiative. The first requirement to smart growth is the recognition of an urban boundary that limits suburbanization. With a firm urban boundary, developers are encouraged to build vertically and to build urban in-fill projects. While construction on greenfield sites away from the core of a city and centers of employment may appear less expensive, the increased densities found in smart growth developments can help spread the costs of land, environmental remediation and infrastructure over a larger number of housing units. Accordingly, these units can be sold at prices that are competitive with, if not lower than, those projects built on greenfields. Smart growth development of this type is additionally beneficial to local communities because the developments are located close to jobs, which in turn reduce housing and commuting expenses. The community is also a beneficiary of smart growth development as the reduction in brownfields, the remediation of pollution and the decrease in traffic improve the quality of life for the citizens of that community.

**Lifting the Cloud**

Population growth in the United States will create 13 million to 15 million new households over the coming decade, creating a need for homebuilders to construct about 1.6 million new homes each year during that same period. These numbers do not account for the millions of rental units and single family homes that this country needs to provide to catch up with the lack of affordable housing supply on the market. While the obstacles to the provision of affordable housing are formidable, through successful public-private partnership arrangements, land use and financial incentives, developers, cities and states can lift the cloud for the more than 28 million Americans who face limited access to decent, safe, affordable housing.

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# 426 June 2002

## EPA's Regulatory Turnaround an Example of Compassionate Conservatism in Action

by Syd Gernstein

Just the thought of new environmental regulations can make people groan. Nobody wants to breathe dirty air or drink toxic water, but government policies to protect the planet can be unnecessarily expensive - especially for those who can least afford it.

Environmental regulations need not ravage our pocketbooks. The U.S. Environmental Protection Agency (EPA) does not always understand this notion, but the Bush Administration does. This is especially fortunate for poor Americans who don't have much money to spare (and who disproportionately are minorities).

During the Clinton Administration, EPA officials proposed new regulations governing storm water runoff that characterized the agency's inability to understand the budgetary restraints of the American people. The EPA's proposal to increase existing standards regarding post-storm runoff of everything from oil and pesticides to dog feces would require new construction projects to include things such as permanent ponds.1 Not only would this raise costs in the short term, but it would also require permanent maintenance. These measures would reportedly reduce all mud - toxic or not - in storm water drains by 80 percent, but they certainly would reduce the economic independence of hundreds of thousands of hard-working Americans.

It's not clear the one-size-fits-all style the EPA advocated at the time would lead to cleaner water. Common sense dictates that towns in the Arizona desert face different runoff challenges than New York City suburbs. Uniform regulations fail to account for such subtleties.

Additionally, and most important to the average American, is that the old EPA leadership's proposed mud policy would add $3,500 to the price of a new home.2 This $3,500 increase could force more than one million lower-income Americans completely out of the housing market.3 In particular, it would stem the rising tide of black homeownership, which recently rose to a record 6.1 million black households owning their own homes.4

It would not likely be any better for renters since landlords would likely pass on regulatory costs through rent increases.

These economic concerns led the Small Business Administration, Office of Management and Budget, Department of Housing and Urban Development (HUD), Department of Transportation and the White House Council of Economic Advisers to all criticize the EPA's proposed storm water runoff regulation. HUD Assistant Secretary John C. Weicher said, "The effect on the rental market is likely to make it harder to achieve the national housing goal of a decent home for all families, and the effect on single-family homes is likely to make it harder for young families to buy their first homes."5

By the way, we already pay for storm water regulations. All existing regulations factor into new home prices to the tune of approximately $5,000. The National Association of Home Builders estimates the regulatory costs of building a house in three major metropolitan areas - Cincinnati, Ohio; Pittsburgh, Pennsylvania and Santa Fe, New Mexico - tripled between 1974 and 1994.6 A main factor driving housing cost increases includes environment-related regulations such as sewer and water fees and storm water runoff controls.

Despite already charging consumers thousands of dollars for storm water regulations, the EPA wanted to impose further restrictions that would yield, in the words of Small Business Administration Chief Counsel for Advocacy Thomas M. Sullivan, "questionable water quality benefits."7

These concerns led the Bush Administration to set aside plans to implement these burdensome storm water runoff regulations. Current EPA Administrator Christine Todd Whitman instead proposed a new policy that relies on states, local governments and the contractors themselves - those most familiar with their neighborhoods - to determine their own polices. By allowing those who know how to keep individual stormwater drains clean, the Whitman EPA has found a less costly, less burdensome and more effective plan.8

This compromise is an embodiment of "compassionate conservatism" the Bush touted while campaigning for the White House. It is a solution that protects the environment without ravaging the pocketbooks of hard-working families.

The Bush White House deserves praise for listening to local concerns and, at least in this instance, not imposing needless regulations that drive Americans, especially the poor and minorities, away from achieving the American Dream of homeownership.

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Syd Gernstein is a research associate of The National Center for Public Policy Research, a Washington, D.C. think tank. Comments may be sent to SGernstein@nationalcenter.org.

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**Footnotes:**

1 "Bush Administration Lets Construction Companies Off the Hook for Protecting Environment," National Resources Defense Council, Washington, DC, May 24, 2002, downloaded from http://www.nrdc.org/bushrecord/water_pollution.asp#589 on July 1, 2002.

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EPA-600/R-02/021
January 2002

# Costs of Urban Stormwater Control

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Contract No. 68-C7-0011

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## Foreword

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threatens human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

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E. Timothy Oppelt, Director
National Risk Management Research
Laboratory

## Abstract

This report presents information on the cost of stormwater pollution control facilities in urban areas, including collection, control, and treatment systems. Information on prior cost studies of control technologies and cost estimating models used in these studies was collected, reviewed, and evaluated. The collection phase involved identifying, screening, and consolidating publications associated with capital costs of stormwater conveyance systems and control technologies. The resulting data were evaluated to develop a critical review of costs for urban stormwater control technologies, including identification of cost information gaps and research needs.

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## Acknowledgments

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# Chapter 1

## Introduction

The purpose of this report is to provide information on the cost of stormwater quantity and quality control facilities. Information on prior cost studies of control technologies and the cost estimating models used in these studies was collected, reviewed, and evaluated as part of this effort. The collection phase involved identifying, screening, and consolidating published literature, papers, reports, etc. associated with capital costs, operation and maintenance costs, performance, and effectiveness of stormwater control technologies. The resulting data were evaluated to develop a preliminary critical review of stormwater control technologies. This review discusses cost-effectiveness, delineates technology gaps, and develops a list of research needs in these areas. The prototype cost model is presented as a spreadsheet model.

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# Chapter 2

# Cost Estimation Methods

## 2.1 Forms of the Cost Equations

### *2.1.1 Single explanatory variable*

The traditional way to present summary results of cost estimation data is to approximate the cost with a single variable power function shown in equation 2.1. This power function is linear in the log transform. Thus, the data should plot as a straight line on log-log paper. The two parameters ($\alpha_0$ and $\alpha_1$) can be estimated from the log-log graph or found using linear regression on the log-transformed data. Contemporary spreadsheets such as Excel fit the function automatically.

$$C = \alpha_0 x^{\alpha_1} \tag{2-1}$$

where

$C$ = cost, \$
$\alpha_0$ = site specific coefficient, e.g., location and land use
$x$ = independent variable, i.e., some measure of component size

The exponent, $\alpha_1$, represents the economies of scale factor. If $\alpha_1$ is less than 1.0, then unit costs decrease as size increases. A generic economies of scale factor that has been used for years is $\alpha_1$ = 0.6 (Peters and Timmerhaus, 1980). When $\alpha_1$ = 1, the power function simplifies to a linear relationship and no economies of scale are present. If $\alpha_1 > 1$, then diseconomies of scale are evident.

A key reason for the popularity of the power function approximation was that it was an efficient way to replace a database with a single equation. This feature was very important before the widespread use of computers. The negative side of this simple approximation is that the fit may not be that accurate. Cost is seldom a function of only one explanatory variable.

### *2.1.2 Multiple explanatory variables*

The cost estimation problem can be expressed in a general form as:

$$C = f(x_1, x_2, \ldots x_i, \ldots x_n) \tag{2-2}$$

where

$C$ = cost, \$
$x_i$ = independent variable that is a measure of component size

If a database of historical cost estimates as a function of $n$ explanatory variables is available, then an approximating equation can be developed using a variety of multiple regression approaches. The most popular form of the estimating equation is simply to use multiple linear regression. However, the relationship of cost to several explanatory variables is seldom this simple.

Below is a review of historical cost relationships for materials of interest to this analysis. These sections illustrate the development of functional forms to match the cost data at the time, and the general development of cost estimation techniques. However, no attempt has been made to update these equations to the present because the results are 20-30 yr. old, and many of the key assumptions and limitations are not presented. All of the regression models presented here assume that the independent variable is exact, i.e., that all the error is in the independent variable, and that the error follows a normal distribution.

## 2.2 Pipe Costs

Dajani et al. (1972) estimated wastewater collection network costs by fitting regression models to data from actual construction bids. The following functional form was assumed:

$$C = a + bD^2 + cX^2 \qquad \textbf{(2-3)}$$

Where

$C$ = construction cost, \$
$D$ = pipe diameter, ft
$X$ = average depth of excavation, ft

Merritt and Bogan (1973) used a graphical relationship to estimate pipe construction cost as a function of diameter and invert depth. No database accompanied this graph. Grigg and O'Hearn (1976) present storm drainage pipe costs as a function of pipe diameter based on data for Englewood, CO. Tyteca (1976) presents cost functions for wastewater conveyance systems. For pipe systems, he uses functions of the following form:

$$C/L = K + aD^b \qquad \textbf{(2-4)}$$

Where

$C$ = total capital cost, \$
$L$ = length of pipe, m
$K$ = fixed cost, \$
$D$ = diameter, m
$a$, $b$ = parameters

According to Tyteca, values of $b$ range from 1.2 to 1.5. For the Belgium case studied by Tyteca (1976), he developed three cost functions depending on whether the terrain is "meadows," "river banks," or a "river in urban area." A positive fixed cost was included in each of these three equations and $b$ ranged from 1.0 to 1.68. These regression equations have little transferability in space or time.

Han, Rao, and Houck (1980) estimated storm drainage costs as part of an optimization model they developed. They used the following equations for estimating storm sewer pipe costs:

For $H \leq 20, D \leq 36$ $$C = 1.93D + 1.688H - 12.6 \tag{2-5}$$

For $H > 20, D \leq 36$ $$C = .692D + 2.14H + .559DH - 13.56 \tag{2-6}$$

For $D > 36$ $$C = 3.638D + 5.17H - 111.72 \tag{2-7}$$

Where

$C$ = installation cost of the pipe, 1980 $/ft
$D$ = diameter, in.
$H$ = invert depth, ft

The U.S. Army Corps of Engineers (1979) MAPS software was the first to use a process engineering oriented approach for estimating the cost of water resources infrastructure. For gravity pipes, MAPS estimated the cost as follows:

The required input is as follows:

- Flow (maximum and minimum), MGD
- Length, ft
- Initial elevation, ft
- Final elevation, ft
- Terrain multipliers
- Design life (default = 50 yr)
- Manning's *n* (default = 0.015)
- Number and depth of drop manholes
- Rock excavation, % of total excavation
- Depth of cover, ft (default = 5 ft)
- Dry or wet soil conditions
- Cost overrides

The average annual cost is calculated as:

$$AAC = AMR + TOTOM \tag{2-8}$$

Where

$AAC$ = average annual cost, $/yr
$AMR$ = amortized capital cost, $/yr
$TOTOM$ = annual O&M cost, $/yr

The amortized capital cost is:

$$AMR = CRF * PW \tag{2-9}$$

Where

$CRF$ = capital recovery factor
$PW$ = capital cost, $

The capital costs are estimated as

$$PW = CC + OVH + PLAND \tag{2-10}$$

Where

$CC$ = construction costs, $
$OVH$ = overhead costs, $
$PLAND$ = land costs, $

Overhead costs are estimated as

$$OVH = 0.25 * CC \tag{2-11}$$

$$CC = AVC * WETFAC * DEPFAC * XLEN * SECI * CITY * CULT * \frac{(1 + Rock * 2)}{255.6} \tag{2-12}$$

Where

$AVC$ = unit cost of pipe for average conditions, $/ft
$WETFAC$ = wetness factor
= 1.2 for wet soil
= 1.0 for average soil
= 0.8 for dry soil

$DEPFAC$ = depth of cover factor

$$= 0.725 + 0.048 * DEPTH \tag{2-13}$$

$DEPTH$ = depth of cover, ft
$XLEN$ = length of pipe, ft
$SECI$ = EPA sewer index (1957-59 = 100)
$CITY$ = city multiplier
$CULT$ = terrain multiplier
$Rock$ = rock excavation percent of total excavation, in decimal form

The EPA sewer index is no longer available. The Engineering News-Record (ENR) Construction Cost Index has been used in this report. The terrain multiplier is calculated as:

$$CULT = \frac{(C1 * 0.8131 + C2 * 0.6033 + C3 * 0.6985 + C4 * 0.7169 + C5 * 0.7911 + C6 * 1.3127)}{100} \tag{2-14}$$

Where

$C1$ = % open country
$C2$ = % new residential
$C3$ = % sparse residential
$C4$ = % dense residential
$C5$ = % commercial
$C6$ = % central city

The MAPS formulation is an interesting blend of regression equations and cost factors. Unfortunately, the database for the regression equations such as for estimating terrain effects was never presented. Thus, the user must take these equations at face value.

Moss and Jankiewicz (1982) promote the use of life cycle costing to determine the best type of storm sewer pipe to buy. For their case study of Winchester, Virginia, three types of sewers were being considered: reinforced concrete (service life = 75 year), aluminum coated steel (service life = 25 year), and asphalt-coated galvanized steel (service life = 20 year). As the authors point out, service life is difficult to estimate. It depends on material durability, in-place structural durability, abrasive characteristics of the drainage, and corrosive characteristics of both ground water and drainage. In the case of different service lives, the comparison should be done using a least common multiple of years, 300 yr in this case. Thus, the present worth is calculated by comparing the cost of the original installation and three replacements for the steel pipe, 11 replacements for the aluminum steel pipe, and 14 replacements for the galvanized steel pipe. The salvage value for each replacement should be included. Alternatively, the equivalent uniform annual cost of each option could be determined with the lowest annual cost used as the decision criterion.

## 2.3 Manholes

For individual manholes, Han, Rao, and Houck (1980) used the following equation:

$$C_m = 259.4 + 56.4h \tag{2-15}$$

Where

$C_m$ = manhole cost, 1980 $
$h$ = depth of manhole, ft

Dames and Moore (1978) estimate manhole costs indirectly as 36 to 38% of the total in-place pipe cost.

## 2.4 Other Sewer Pipe Related Costs

Dames and Moore (1978) present estimates of added costs associated with sanitary sewer pipes. Their results are shown in Table 2-1. The above results indicate the vital importance of site-specific cost data since the total additional cost is over 100%.

**Table 2-1. Average Non-Pipe Costs as Percent of Total In-Place Pipe Costs for Sanitary Sewers (Dames and Moore, 1978)**

| Category | Pipe Cost (%) |
|---|---|
| Sanitary sewer miscellaneous appurtenances | 7 |
| Manholes | 32 |
| Drop manholes | 2 |
| Thoroughfare crossings | 13 |
| Stream crossings | 1 |
| Rock excavation | 2 |
| Pavement removal and replacement | 13 |
| Special bedding | 1 |
| Miscellaneous costs not categorized | 28 |
| Utility reconnection and removal | 1 |
| Total | 100 |

## 2.5 Storage Costs

Storage is used to detain or retain peak stormwater flows for later release at a slower rate. Storage can improve or degrade downstream water quality, depending upon how it is operated. Stahre and Urbonas (1993) present a detailed evaluation of urban stormwater storage systems. Nix and Heaney (1988) show how to find the optimal mix of storage and release or treatment rate.

Storage costs depend heavily upon land costs. Land costs range from zero, if the land is assumed part of an easement or "donated" by the developer, to "full costs," based on the highest alternative use of the land. A summary of selected storage cost estimation equations is presented in Table 2-2.

Inspection of the storage estimating equations reveals that the economies of scale factor ranges from a low of 0.40 for large reservoirs to a high of 0.83 for a combined sewer overflow (CSO) storage basin. In addition, earthen basins cost less than 10% of the cost of the same size concrete basin.

## 2.6 Multipurpose Facilities

The cost of storm drainage systems is affected by other purposes that the system serves. For example, a combined sewer system provides the dual purposes of transporting both wastewater and stormwater. Storm drainage systems provide local flood control but may exacerbate water quality problems and degrade downstream receiving waters.

Stormwater detention systems may serve as both quantity and quality controls. Streets serve as traffic conduits and transport stormwater. An acceptable way to apportion the costs of a multipurpose facility to individual purposes is to design systems for each purpose independently, and then design the multipurpose system. The go-it-alone costs and the costs for the multipurpose facility are prorated to determine the apportioned costs (Heaney, 1997).

**Table 2-2. Estimated Capital Cost of Storage as a Function of Volume**

| Type | Equation | *C* ($ Units) | *V* (Range) | *V* (Units) | Year | Reference |
|---|---|---|---|---|---|---|
| Reservoir | $C = 160V^{0.4}$ | 1,000 | $10^4 - 10^6$ | Acre-ft | 1980 | 1 |
| Covered concrete tank | $C = 614V^{0.81}$ | 1,000 | 1–10 | Mgal | 1976 | 2 |
| Concrete tank | $C = 532V^{0.61}$ | 1,000 | 1–10 | Mgal | 1976 | 2 |
| Earthen basin | $C = 42V^{0.61}$ | 1,000 | 1–10 | Mgal | 1976 | 2 |
| Clear well, below ground | $C = 495V^{0.61}$ | 1,000 | 1–10 | Mgal | 1980 | 2 |
| Clear well, ground level | $C = 275V^{0.61}$ | 1,000 | 0.01–10 | Mgal | 1980 | 2 |
| CSO storage basin | $C = 3637V^{0.83}$ | 1,000 | 0.15–30 | Mgal | 1993 | 2 |
| CSO deep tunnel | $C = 4982V^{0.80}$ | 1,000 | 1.8–2,000 | Mgal | 1993 | 3 |

*C* = capital cost; *V* = volume
References: [1]U.S. Army Corps of Engineers (1981); [2]Gummerman et al. (1979); [3]U.S. EPA (1993b)

## 2.7 Integrated Approaches

Rawls and Knapp (1972) gathered data from 70 stormwater systems in the United States and used linear and nonlinear regression analysis to estimate total system costs as a function of the explanatory variables shown below:

- Recurrence interval, yr
- Average ground slope, ft/100 ft
- Runoff coefficient, C
- Number of manholes and inlets
- Smallest pipe size, in.
- Largest pipe size, in.
- Total capacity, $ft^3/s$
- Total length of lines, ft
- Total drainage area, acre
- Total developed area, acre

This approach is useful for aggregate comparative analysis among cities but the results are quite dated.

Earle and Farrell (1997) recently presented a mathematical model for estimating sanitary sewer costs. They used construction cost data from R.S. Means "Site Work and Landscape Cost Data." The output of their model is an estimate of the average cost per house for the collection system under study. The following factors are used to estimate the final cost per house:

| | | |
|---|---|---|
| City Cost Index | K1 | .85 – 1.12 |
| Bidding Conditions Factor | K2 | .95 – 1.05 |
| Hazen Williams "C" Factor | K3 | 1.0 – 1.04 |
| Restoration Complexity | K4 | .85 – 1.25 |
| Location (in or out of right-of-way) | K5 | 1.0 – 1.05 |
| Soil Conditions (influence of rock) | K6 | 1.0 – 1.75 |
| Ground Water | K7 | 1.0 – 1.26 |

By selecting values of each of the above seven factors (K), the final cost per house is estimated as:

$$C_{final} = C_{base}(K1 * K2 * K3 * K4 * K5 * K6 * K7) \tag{2-16}$$

This approach is a big improvement over the regression approach. The R.S. Means database is a reliable source of current information on sewer costs. The use of factors is a way to incorporate site attributes. The major limitation of this approach is that factor selection remains subjective. For example, the Soil Conditions Factor varies from 1.0 to 1.75. Which value should we choose? The effect of rock depends not only on its presence but also on its location in the pipe network.

### 2.8 Process-Oriented Approaches

In a process-oriented approach, the cost estimation model is linked directly to a process simulator. In the case of urban stormwater, the cost model can be linked directly to the hydrologic and hydraulic simulators. The only current model we found that incorporates this feature is the HYDRA computer program available as part of the Federal Highway Administration's HYDRAIN program (FHWA 1991). This model only does simple links between pipe costs and an assumed design. Storm sewer optimization is not included.

### 2.9 Stormwater Cost Optimization

While accurate cost data are essential for cost estimation, the total project cost depends heavily upon the quality of the selected solution. Various optimization techniques for finding the optimal design for a stormwater drainage system have been proposed, but because of the inherent complexity of the problem these classical optimization approaches have had very limited success.

Literature on this subject has been reviewed by Miles and Heaney (1988) who present a spreadsheet-based trial and error approach for solving the problem. A profile view of the vertical alignment of a stormwater drainage system is shown in Figure 2-1 (Miles and Heaney, 1988). The basic tradeoff is that between pipe and excavation costs. The larger the pipe diameter, the shallower the slope that can be used, reducing excavation costs, albeit at the expense of additional pipe costs.

Miles and Heaney (1988) reanalyzed the twenty-pipe problem shown in Figure 2-2. They were able to demonstrate that the spreadsheet method provided a superior solution because it depicted the pipe hydraulics more accurately and used a relatively efficient trial and error procedure. For each trial, the spreadsheet calculates the total cost of the design and checks to see whether the design constraints have been satisfied.

The problem is actually relatively complex. Typically, the drainage network must discharge at a specified elevation at the outfall. For each section, the designer must select from 8 to 10 pipe diameters among a large range of pipe slopes. If 10 pipe diameters and 10 slopes are available at each section, then 100 possible combinations need to be checked. If one starts at the headwaters, then the calculations can proceed relatively easily until this branch intersects another branch. For example, we can design branches 12-32 and 32-42 in Figure 2-2. Similarly, we can design branches 11-22, 22-33, and 33-42. However, the two independently designed branches may result in different invert elevations at node 42. The invert elevation for node 42 affects the cost of the entire downstream pipe network. Thus, we quickly end up with thousands of possible combinations to evaluate. Conventional designers typically evaluate very few options and then stop once they have found a feasible solution.

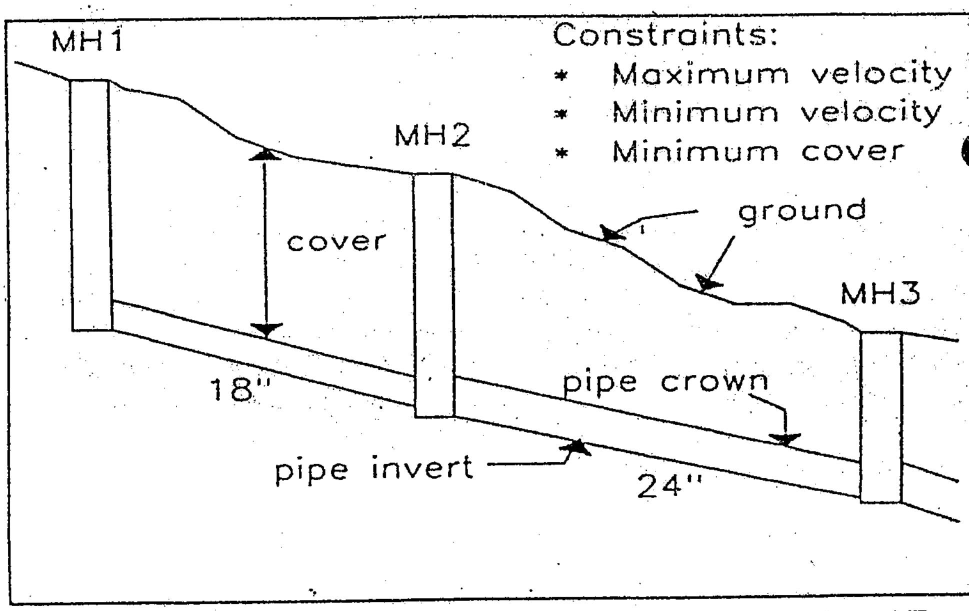



**Figure 2-1. Profile view of the vertical alignment of a stormwater system (Miles and Heaney, 1988) (Reproduced with permission of the American Society of Civil Engineers).**

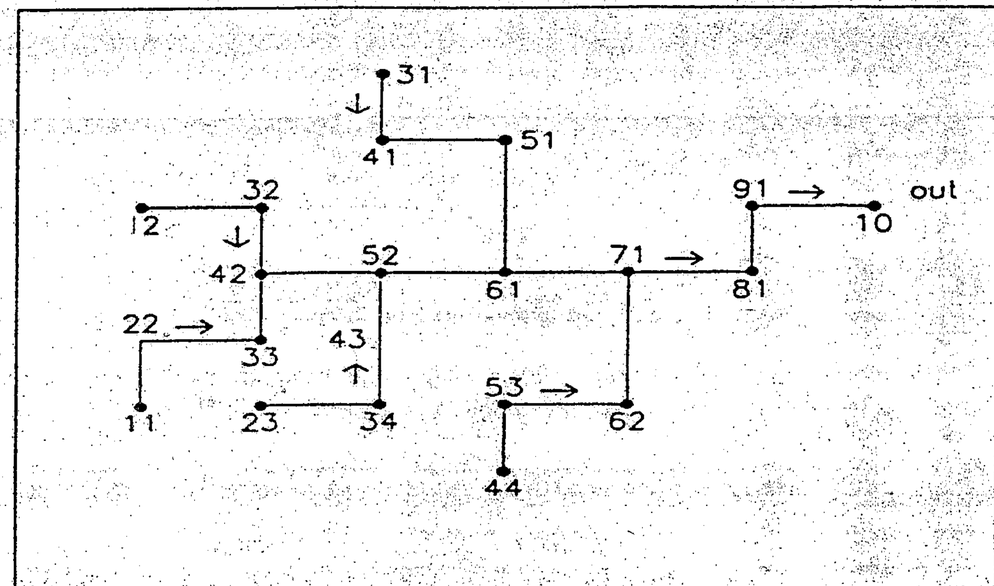



Figure 2-2. Layout of the twenty pipe stormwater problem (Miles and Heaney, 1988) (Reproduced with permission of the American Society of Civil Engineers).

Because existing designs are not optimized, it is difficult to compare them. It is also difficult to do sensitivity analysis because we don't know how good the solutions are. The lack of a systematic way to optimize sewer design is a major impediment for improved cost-effectiveness evaluations. We have developed a new way to do this evaluation using intelligent search techniques (Heaney et al., 1998d).

## 2.10 Summary and Conclusions

Virtually all cost estimates in the literature are based on the conventional approach of fitting regression equations to cross sectional data on "as-builts." Before the widespread availability of microcomputers, these approaches were the only viable alternative. Unfortunately, even since the advent the personal computer, little research funding has been available to develop the databases necessary for detailed cost estimation procedures. Curve fitting methods are inefficient given the available technology for computerized design calculations. An improved method is to link the cost estimator directly to the hydraulic simulator, and then develop cost estimates relative to the fundamental processes of an urban drainage system.

## Chapter 3

## Cost Estimates for Stormwater Systems

The goal of this section is to provide the tools and data necessary to accurately estimate the costs of conventional stormwater systems; pipeline installation; excavation; bedding, and manhole installation. Section on open channels, storage, pumps, and paving costs are included as well for future reference

### 3.1 Stormwater Pipelines

This section describes the cost components of pipeline installation, i.e.:

1. Pipeline Installation: The pipelines themselves, and the material, labor, and equipment necessary for installation.
2. Trench Excavation Costs: The cost of excavating and constructing the trench into which the pipeline is installed. Backfill and rock blasting are included within this category.
3. Bedding Costs: These include the material, labor, and equipment necessary to install a simple compacted bedding system prior to backfilling the trench.

#### *3.1.1 Pipeline installation*

The costs of two different types of pipe were tabulated based on the data from RS Means (1996a). All values are updated to 1/99 $ using the ENR index of 6000 for January 1999, and 5584 for July 1995. The costs include fixed operations cost and profit, and the pipe materials, labor, and equipment. Because of the relative cost of the materials, pipes typically chosen for stormwater systems are corrugated metal (CMP), and reinforced concrete (RCP). The RS Means data was chosen for this analysis because of the longevity of this source of data (the user of this spreadsheet can easily swap databases, however).

A plot of the total installed costs (excluding excavation and backfill) vs pipe diameter for the CMP and RCP pipes is shown in Figure 3-1. A nonlinear relationship is readily apparent, and a power function was fit to the data. The resulting equation below is for CMP pipe, using the updated RS Means data:

$$C_p = 0.54D^{1.3024} \qquad \textbf{(3-1)}$$

Where

$C_p$ = construction cost, 1/99 $/ft

$D$ = pipe diameter, in.

Although Equation 3.1 has a relatively high correlation coefficient ($R^2$) of .98, it is not a close fit for larger pipe diameters. A better way to estimate pipe costs is to use a lookup table, which is a standard feature in spreadsheets. Lookup tables are particularly useful for discrete data such as pipe diameters, and avoid the problem of trying to find a single equation that fits well over a wide range of pipe sizes.

The lookup tables for the design model is shown as Tables 3-1 and 3-2 for CMP and RCP pipe, respectively. A major disadvantage of using equations instead of direct cost data can be seen in Figure 3-1. The power function, although providing a good overall fit, can deviate from the actual cost/ft data point significantly, leading to an underestimation of project costs. However, an important advantage is that the equations provide a shorthand method of storing the relationship between costs and capacity. Equations facilitate the economic analytical evaluation of the component under consideration. With the use of a spreadsheet model, however, it becomes less necessary to make simplifying assumptions necessary to make regression fits possible, because simple lookup functions can replace these approximating equations.

**Table 3-1. Lookup Table for Corrugated Metal Pipe (updated from RS Means, 1996a)**

| Diameter (in.) | Cost (1/99 $/ft) |
|---|---|
| 8 | 9.40 |
| 10 | 11.80 |
| 12 | 14.40 |
| 15 | 18.40 |
| 18 | 20.90 |
| 24 | 30.10 |
| 30 | 37.20 |
| 36 | 54.80 |
| 48 | 81.60 |
| 60 | 118.20 |
| 72 | 179.50 |

**Table 3-2. Lookup Table for Reinforced Concrete Pipe (updated from RS Means, 1996a)**

| Diameter (in.) | Cost (1/99 $/ft) |
|---|---|
| 12 | 15.70 |
| 15 | 16.60 |
| 18 | 19.00 |
| 21 | 23.00 |
| 24 | 27.60 |
| 27 | 32.90 |
| 30 | 55.80 |
| 36 | 74.40 |
| 42 | 85.40 |
| 48 | 102.30 |
| 60 | 146.70 |
| 72 | 192.60 |
| 84 | 288.90 |
| 96 | 355.60 |

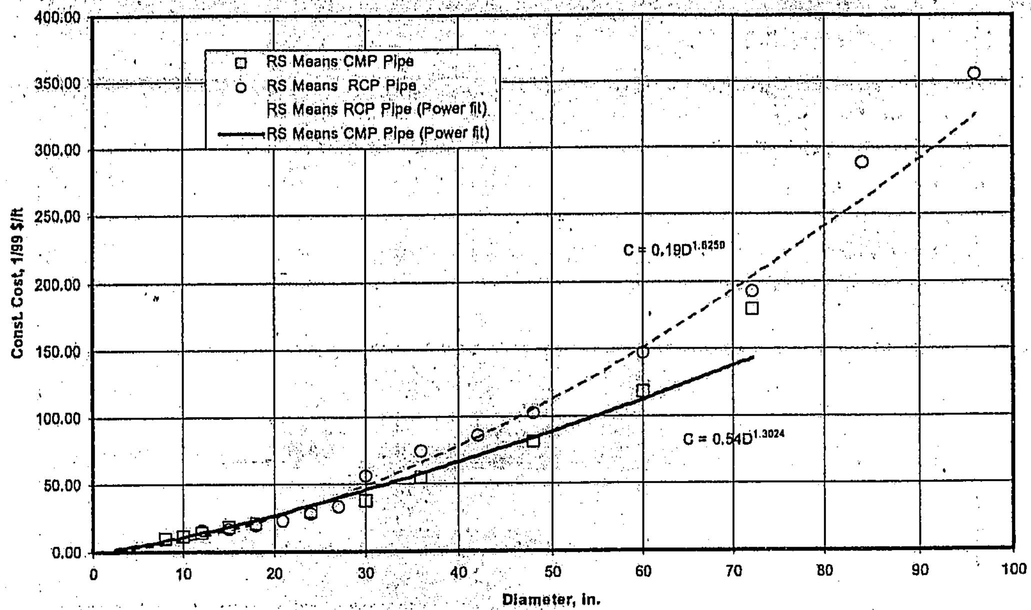



**Figure 3-1. Cost of storm drainage pipe.**

### *3.1.2 Trench excavation costs*

Various trench excavation cost data were updated from RS Means (1996a) and plotted in Figure 3-2. Included are such fixed operations costs as labor, equipment, and materials costs. Although the excavation costs generally vary with depth and backhoe bucket size (not shown here), there was no statistical relationship that could explain this variation easily. For the purposes of the model, an average of this data was taken, which results an average excavation cost in $/yd$^3$ for a "moist loam" type of soil. Then, using productivity estimates from RS Means (1996a) for various soils, the excavation costs in Table 3-3 were obtained.

**Table 3-3. Trench Excavation Costs, Includes Backfill and Blasting (updated from RS Means, 1996a)**

| Soil Type | Horizontal | Vertical | Excavation Cost (1/99 $/yd$^3$) |
|---|---|---|---|
| Clay | 1 | 1 | 7.09 |
| Moist loam | 2 | 1 | 5.87 |
| Rock | 0 | 1 | 86.29 |
| Sand | 2 | 1 | 6.12 |
| Silt | 1.5 | 1 | 6.72 |

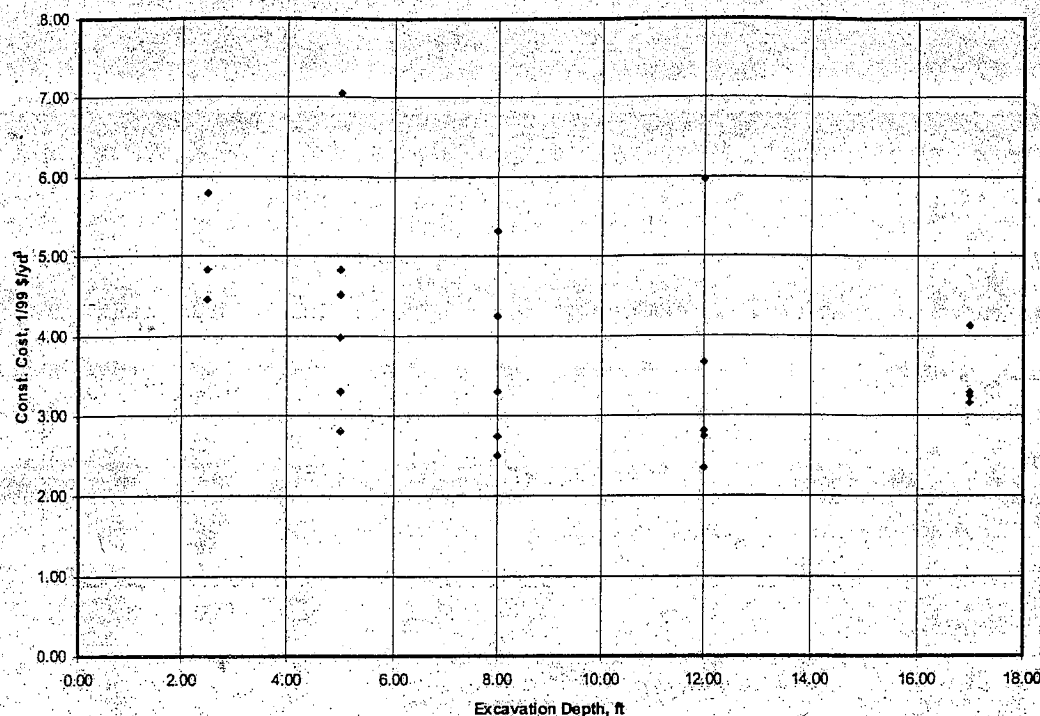



**Figure 3-2. Trench excavation costs (Updated from RS Means, 1996a).**

### *3.1.3 Bedding costs*

Bedding provides sufficient compacted material necessary to protect the pipe from external loading forces. Bedding costs in the RS Means (1996a) system vary with diameter and side slope of the trench. The bedding material is compacted bank sand filled to 12 in. above the pipe. These costs were updated to 1/99 $ and can be found in Table 3-4. This table relates the horizontal and vertical side slope, the diameter, and the width to bedding costs, which include fixed operations cost and profit. Although several regression relationships were evaluated, it was decided that the most accurate model of these costs would be a two-way lookup table, relating the horizontal:vertical ratio and the pipe diameter to the projected cost.

Table 3-4. Bedding Costs (updated from RS Means, 1996a)

| Horizontal | Vertical | H/V | Diameter (in.) | Trench Width (ft) | Cost (1/99 $/ft) |
|---|---|---|---|---|---|
| 0 | 1 | 0 | 6 | 1 | 0.92 |
| 0 | 1 | 0 | 8 | 2 | 2.00 |
| 0 | 1 | 0 | 10 | 2 | 2.07 |
| 0 | 1 | 0 | 12 | 2 | 2.12 |
| 0 | 1 | 0 | 14 | 3 | 3.47 |
| 0 | 1 | 0 | 15 | 3 | 3.51 |
| 0 | 1 | 0 | 16 | 3 | 3.57 |
| 0 | 1 | 0 | 18 | 3 | 3.62 |
| 0 | 1 | 0 | 20 | 4 | 5.25 |
| 0 | 1 | 0 | 21 | 4 | 5.29 |
| 0 | 1 | 0 | 24 | 4 | 5.44 |
| 0 | 1 | 0 | 30 | 4 | 5.55 |
| 0 | 1 | 0 | 32 | 6 | 9.72 |
| 0 | 1 | 0 | 36 | 6 | 9.98 |
| 0 | 1 | 0 | 48 | 7 | 13.01 |
| 0 | 1 | 0 | 60 | 8 | 16.23 |
| 0 | 1 | 0 | 72 | 10 | 23.39 |
| 0 | 1 | 0 | 84 | 12 | 31.80 |
| 0.5 | 1 | 0.5 | 6 | 1 | 1.90 |
| 0.5 | 1 | 0.5 | 8 | 2 | 3.16 |
| 0.5 | 1 | 0.5 | 10 | 2 | 3.43 |
| 0.5 | 1 | 0.5 | 12 | 2 | 3.67 |
| 0.5 | 1 | 0.5 | 14 | 3 | 5.25 |
| 0.5 | 1 | 0.5 | 15 | 3 | 5.39 |
| 0.5 | 1 | 0.5 | 16 | 3 | 5.55 |
| 0.5 | 1 | 0.5 | 18 | 3 | 5.88 |
| 0.5 | 1 | 0.5 | 20 | 4 | 7.77 |
| 0.5 | 1 | 0.5 | 21 | 4 | 7.95 |
| 0.5 | 1 | 0.5 | 24 | 4 | 8.52 |
| 0.5 | 1 | 0.5 | 30 | 4 | 9.56 |
| 0.5 | 1 | 0.5 | 32 | 6 | 14.06 |
| 0.5 | 1 | 0.5 | 36 | 6 | 15.08 |
| 0.5 | 1 | 0.5 | 48 | 7 | 20.58 |
| 0.5 | 1 | 0.5 | 60 | 8 | 26.81 |
| 0.5 | 1 | 0.5 | 72 | 10 | 37.47 |
| 0.5 | 1 | 0.5 | 84 | 12 | 49.71 |
| 1 | 1 | 1 | 6 | 1 | 2.90 |
| 1 | 1 | 1 | 8 | 2 | 4.36 |
| 1 | 1 | 1 | 10 | 2 | 4.77 |
| 1 | 1 | 1 | 12 | 2 | 5.25 |
| 1 | 1 | 1 | 14 | 3 | 7.06 |
| 1 | 1 | 1 | 15 | 3 | 7.30 |
| 1 | 1 | 1 | 16 | 3 | 7.56 |
| 1 | 1 | 1 | 18 | 3 | 8.14 |
| 1 | 1 | 1 | 20 | 4 | 10.28 |
| 1 | 1 | 1 | 21 | 4 | 10.59 |
| 1 | 1 | 1 | 24 | 4 | 11.61 |
| 1 | 1 | 1 | 30 | 4 | 13.50 |
| 1 | 1 | 1 | 32 | 6 | 18.46 |
| 1 | 1 | 1 | 36 | 6 | 20.17 |
| 1 | 1 | 1 | 48 | 7 | 28.17 |
| 1 | 1 | 1 | 60 | 8 | 37.40 |
| 1 | 1 | 1 | 72 | 10 | 51.76 |
| 1 | 1 | 1 | 84 | 12 | 67.70 |
| 1.5 | 1 | 1.5 | 6 | 1 | 3.91 |
| 1.5 | 1 | 1.5 | 8 | 2 | 5.69 |
| 1.5 | 1 | 1.5 | 10 | 2 | 6.15 |
| 1.5 | 1 | 1.5 | 12 | 2 | 6.81 |
| 1.5 | 1 | 1.5 | 14 | 3 | 8.83 |

| Horizontal | Vertical | H/V | Diameter (in.) | Trench Width (ft) | Cost (1/99 $/ft) |
|---|---|---|---|---|---|
| 1.5 | 1 | 1.5 | 15 | 3 | 9.18 |
| 1.5 | 1 | 1.5 | 16 | 3 | 9.56 |
| 1.5 | 1 | 1.5 | 18 | 3 | 10.38 |
| 1.5 | 1 | 1.5 | 20 | 4 | 12.80 |
| 1.5 | 1 | 1.5 | 21 | 4 | 13.24 |
| 1.5 | 1 | 1.5 | 24 | 4 | 14.63 |
| 1.5 | 1 | 1.5 | 30 | 4 | 17.64 |
| 1.5 | 1 | 1.5 | 32 | 6 | 22.77 |
| 1.5 | 1 | 1.5 | 36 | 6 | 25.23 |
| 1.5 | 1 | 1.5 | 48 | 7 | 35.76 |
| 1.5 | 1 | 1.5 | 60 | 8 | 48.21 |
| 1.5 | 1 | 1.5 | 72 | 10 | 65.65 |
| 1.5 | 1 | 1.5 | 60 | 8 | 48.21 |
| 1.5 | 1 | 1.5 | 72 | 10 | 65.65 |
| 1.5 | 1 | 1.5 | 84 | 12 | 86.16 |
| 2 | 1 | 2 | 6 | 1 | 5.01 |
| 2 | 1 | 2 | 8 | 2 | 6.73 |
| 2 | 1 | 2 | 10 | 2 | 7.49 |
| 2 | 1 | 2 | 12 | 2 | 8.37 |
| 2 | 1 | 2 | 14 | 3 | 10.59 |
| 2 | 1 | 2 | 15 | 3 | 11.04 |
| 2 | 1 | 2 | 16 | 3 | 11.54 |
| 2 | 1 | 2 | 18 | 3 | 12.66 |
| 2 | 1 | 2 | 20 | 4 | 15.32 |
| 2 | 1 | 2 | 21 | 4 | 15.89 |
| 2 | 1 | 2 | 24 | 4 | 17.71 |
| 2 | 1 | 2 | 31 | 4 | 21.61 |
| 2 | 1 | 2 | 32 | 6 | 27.15 |
| 2 | 1 | 2 | 36 | 6 | 30.22 |
| 2 | 1 | 2 | 48 | 7 | 43.22 |
| 2 | 1 | 2 | 60 | 8 | 58.67 |
| 2 | 1 | 2 | 72 | 10 | 79.32 |
| 2 | 1 | 2 | 84 | 12 | 103.94 |

### 3.2 Manholes

Manhole cost data, updated from RS Means (1996a), are tabulated in Table 3-5. The costs include fixed operations cost and profit, and labor, equipment, and materials costs for installation of precast concrete manholes. A plot of this data can be found in Figure 3-3. A power relationship was plotted and the following equation obtained:

$$C_{mh} = 482H^{0.9317} \qquad \textbf{(3-2)}$$

Where

$C_{mh}$ = cost of manhole, 1/99 $

$H$ = height of manhole, ft (maximum difference between the ground elevation and the invert elevations of sewers entering the manhole)

In general, the fit of the power equation was good, particularly at the lower heights. Some inaccuracies are introduced due to the regression relationship, however this is mitigated by the desire within the system model for a continuous function providing cost as a function of $H$. An alternative method is to use a lookup table and interpolate between the values of Table 3-5.

Table 3-5. Precast Concrete Manholes Costs (updated from RS Means, 1996a)

| Riser Internal Diameter (ft) | Depth (ft) | Cost (1/99 $/ft) |
|---|---|---|
| 4 | 4 | 1,860 |
| 4 | 6 | 2,460 |
| 4 | 8 | 3,250 |
| 4 | 10 | 3,970 |
| 4 | 12 | 4,830 |
| 4 | 14 | 6,060 |
| 5 | 4 | 2,310 |
| 5 | 6 | 3,120 |
| 5 | 8 | 3,970 |
| 5 | 10 | 5,070 |
| 5 | 12 | 6,260 |
| 5 | 14 | 7,600 |
| 6 | 4 | 3,150 |
| 6 | 6 | 4,070 |
| 6 | 8 | 5,340 |
| 6 | 10 | 6,710 |
| 6 | 12 | 8,350 |
| 6 | 14 | 9,990 |

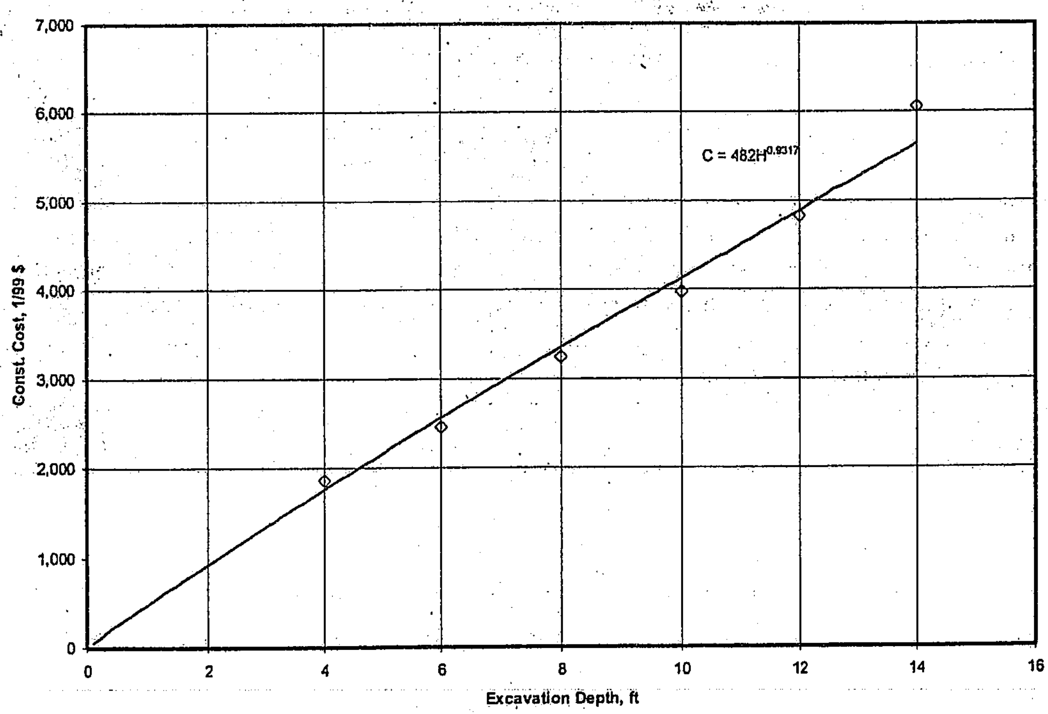



Figure 3-3. Manhole costs, as a function of excavation depth.

## 3.3 Open Channels

The cost of open channels needs to be estimated on a case by case basis since cut and fill calculations are required. Excavation costs are an important component of the construction of an open channel. MAPS (US Army Corps of Engineers, 1979) provides a general template for doing these calculations. The data presented in Table 3-3 on excavation costs may assist in this effort.

## 3.4 Pump Stations

Two different sized sewage pump stations are available in the RS Means database, as shown in Table 3-6. The costs include fixed operations cost and profit, and labor, equipment, and materials costs. An alternative method for calculating a pump station cost would be to develop a generic design of the structure that would be scaled based upon capacity and head, and include the appropriate pump costs. This work is beyond the scope of this effort.

**Table 3-6. Capital Costs of Sewage Pump Stations (updated from RS Means, 1996a)**

| Description | Flow Rate (gpm) | Cost (1/99 $) |
|---|---|---|
| Sewage Pump Station | 200 | 59,000.00 |
| Sewage Pump Station | 1000 | 112,000.00 |

## 3.5 Pavement and Creation of Impervious Surfaces

Fairly good data are available on the cost of various types of pavement, including porous pavement. Table 3-7 lists the main activities associated with paving and creation of impervious areas within developments. The costs include fixed operations cost and profit, and labor, equipment, and materials costs. An example of the use of this data is the following: Using a 32 ft wide subdivision street, with 6 in. crushed stone base material of 1½ in. in diameter, a primer, and a wearing course of 1½ in. of asphaltic concrete pavement, and curb and gutter (both sides) sums to a total of $58.80 per linear foot of pavement. This is shown below:

Base course: $$5.85\frac{\$}{yd^2}*\frac{yd^2}{9\,ft^2}*32\,ft = 20.80\ \$/ft \quad (3\text{-}3)$$

Prime: $$2\frac{gal}{yd^2}*1.82\frac{\$}{gal}*\frac{yd^2}{9\,ft^2}*32\,ft = 12.94\ \$/ft \quad (3\text{-}4)$$

Paving: $$3.14\frac{\$}{yd^2}*\frac{yd^2}{9\,ft^2}*32\,ft = 11.16\ \$/ft \quad (3\text{-}5)$$

Curb: $$6.95\ \$/ft * 2 = 13.90\ \$/ft \quad (3\text{-}6)$$

Total per linear ft: $$\$20.80+\$12.94+\$11.16+\$13.90=\$58.80 \quad (3\text{-}7)$$

Table 3-7. Paving Costs (updated from RS Means, 1996a)

| Activity | Material | Diameter (in.) | Unit | Depth (in.) | Cost (1/99 $) |
|---|---|---|---|---|---|
| Prepare and Roll Subbase >2500 $yd^2$ | | | $yd^2$ | | 0.88 |
| Base Course | Crushed Stone | 0.75 | $yd^2$ | 3 | 3.39 |
| Base Course | Crushed Stone | | $yd^2$ | 6 | 6.07 |
| Base Course | Crushed Stone | | $yd^2$ | 9 | 8.92 |
| Base Course | Crushed Stone | | $yd^2$ | 12 | 11.49 |
| Base Course | Crushed Stone | 1.5 | $yd^2$ | 4 | 3.52 |
| Base Course | Crushed Stone | | $yd^2$ | 6 | 5.85 |
| Base Course | Crushed Stone | | $yd^2$ | 8 | 7.82 |
| Base Course | Crushed Stone | | $yd^2$ | 12 | 12.36 |
| Base Course | Bank run gravel | | $yd^2$ | 6 | 2.63 |
| Base Course | Bank run gravel | | $yd^2$ | 9 | 3.22 |
| Base Course | Bank run gravel | | $yd^2$ | 12 | 5.10 |
| Base Course | Bituminous concrete | | $yd^2$ | 4 | 8.37 |
| Base Course | Bituminous concrete | | $yd^2$ | 6 | 12.04 |
| Base Course | Bituminous concrete | | $yd^2$ | 8 | 15.86 |
| Base Course | Bituminous concrete | | $yd^2$ | 10 | 19.58 |
| Prime and seal | | | gal | | 1.82 |
| Asphaltic Concrete Pavement | Binder Course | | $yd^2$ | 1.5 | 3.14 |
| Asphaltic Concrete Pavement | Binder Course | | $yd^2$ | 2 | 4.09 |
| Asphaltic Concrete Pavement | Binder Course | | $yd^2$ | 3 | 5.91 |
| Asphaltic Concrete Pavement | Binder Course | | $yd^2$ | 4 | 7.77 |
| Asphaltic Concrete Pavement | Wearing Course | | $yd^2$ | 1 | 2.31 |
| Asphaltic Concrete Pavement | Wearing Course | | $yd^2$ | 1.5 | 3.44 |
| Asphaltic Concrete Pavement | Wearing Course | | $yd^2$ | 2 | 4.52 |
| Asphaltic Concrete Pavement | Wearing Course | | $yd^2$ | 2.5 | 5.47 |
| Asphaltic Concrete Pavement | Wearing Course | | $yd^2$ | 3 | 6.51 |
| Curb and Gutter, machine formed | Concrete | 24 | LF | | 6.95 |

Note: gal = gallon; $yd^2$ = square yards; LF = linear foot.

This unit cost ($/ft) is for a lightly traveled subdivision street. As the projected traffic increases, the thickness used increases, thereby increasing the cost per linear foot.

This data is presented so that the cost of transportation related impervious surfaces is included in the system model.

### 3.6 Conclusions

In summary, detailed databases exist that can provide accurate cost information. The use of lookup tables, database functions, and regression (limited use where appropriate), a system model providing generic costing relationships can be built. Systematic evaluation of different designs through simulation enables repeated testing of various designs, leading to a method for optimization.

## Chapter 4

## Cost Effectiveness of Stormwater Quality Controls

### 4.1 Objectives of Control

Stormwater quality control is used to reduce pollutant loadings from urban runoff events. In most cases, the volume and peak flow of the event has a direct bearing on the discharge quality. Some facilities, where the local regulatory focus was on peak flow reduction are now being reevaluated for quality control as well.

### 4.2 Control Descriptions and Construction Costs

Predominant stormwater quality controls are outlined in the following sections and available cost information on them is provided. Detailed cost data were not available for most of these systems, and so design guidance cost curves were updated from several references. This approach would be more viable if the sample size was large. However, the sample sizes are not available for the bulk of these data.

#### *4.2.1 Offline storage-release systems*

Storage-release systems are designed to intercept effluent and retain it for a predetermined time-period prior to its discharge into receiving waters. Before the effluent is released from the storage unit, it has undergone some physical settling, and, perhaps some biological treatment. The two main types of storage systems evaluated here are surface storage and deep tunnels.

4.2.1.1 Surface storage

Surface storage units are offline storage, at or near the surface, and are typically made of concrete. Typically, large diameter culverts are used. The best source of empirical cost data on surface storage can be found in US EPA (1993), which relates cost as a function of size, or volume of the facility. This relationship has been updated to 1/99 $ and is found in equation 4.1:

$$C = 4.546V^{0.826} \tag{4-1}$$

Where

$C$ = construction cost, millions 1/99 $

$V$ = volume of storage system, Mgal (where $0.15 \le V \le 30$ Mgal)

Equation 4.1 has been plotted in Figure 4-1 for the applicable range of volumes.

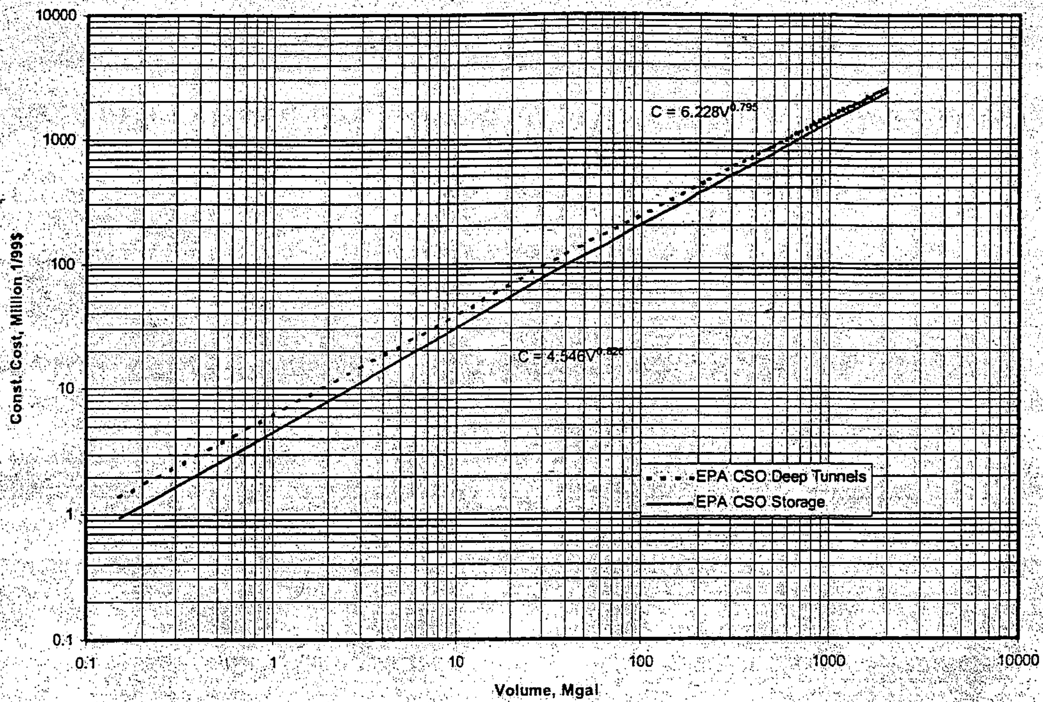



**Figure 4-1. Construction costs of offline storage. (Updated to 1/99 \$, ENR = 6000, Adapted from US EPA, 1993)**

4.2.1.2 Deep tunnels

Deep tunnels, bored into bedrock have been used increasingly in urban areas because space is unavailable for surface storage units. Although they function similarly to surface storage units it is difficult to add biological treatment enhancements or baffling to tunnels. US EPA (1993) is currently the best source of data on the cost of deep tunnels. This source relates cost as a function of size, or storage volume. This relationship has been updated to 1/99 \$ and is expressed in equation 4.2:

$$C = 6.228V^{0.795} \qquad \textbf{(4-2)}$$

Where

$C$ = construction cost, million 1/99 \$
$V$ = volume of storage system, Mgal (where $1.8 \le V \le 2{,}000$ Mgal)

Equation 4.2 has been plotted in Figure 4-1 for the applicable range of volumes.

### *4.2.2 Swirl concentrators*

Swirl concentrators use centrifugal force and gravitational settling to remove the heavier sediment particles and floatables from urban runoff. They are typically used in CSO situations, but may also be used in general urban runoff events (US EPA 1993). These devices alone do not provide any means to reduce peak discharge, they are commonly used in conjunction with some form of storage, and their performance varies (Urbonas, 1999).

The best source of data on swirl concentrators is currently US EPA (1993), which relates cost as a function of size, or, in this case, design flow. This relationship has been updated to 1/99 \$ and is expressed in equation 4.3:

$$C = 0.22Q^{0.611} \qquad \textbf{(4-3)}$$

Where

$C$ = construction cost, millions 1/99 \$
$Q$ = design flow rate, MGD (where $3 \leq Q \leq 300$ MGD)

Equation 4.3 has been plotted in Figure 4-2 for the applicable range of flows.

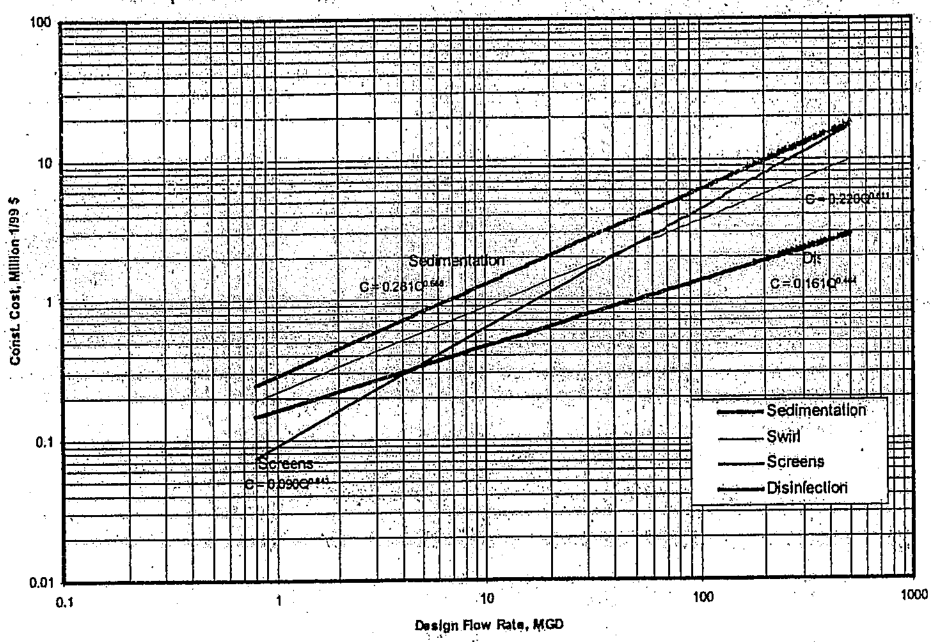



**Figure 4-2. Construction costs for swirl concentrators, screens, sedimentation basins, and disinfection. (Updated to 1/99 \$, ENR = 6000, Adapted from US EPA, 1993).**

### *4.2.3 Screens*

Coarse screens are used to remove large solids and some floatables from CSO discharges. US EPA (1993) is the best current source of available cost data. Cost is expressed as a function of size, or design flow. This relationship has been updated to 1/99 $ and is shown in equation 4.4:

$$C = 0.09Q^{0.843} \tag{4-4}$$

Where

$C$ = construction cost, millions 1/99 $

$Q$ = design flow rate, MGD (where $0.8 \leq Q \leq 200$ MGD)

Equation 4.4 has been plotted in Figure 4-2 for the applicable range of flows.

### *4.2.4 Sedimentation basins*

Sedimentation basins detain stormwater to allow physical settling prior to its discharge. These basins are usually baffled to eliminate short circuiting of the flow. US EPA (1993) is the best current source of cost data on sedimentation basins. This source relates cost as a function of size, or design flow. The relationship has been updated to 1/99 $ and is expressed in equation 4.5:

$$C = 0.281Q^{0.668} \tag{4-5}$$

Where

$C$ = construction cost, millions 1/99 $

$Q$ = design flow rate, MGD (where $1 \leq Q \leq 500$ MGD)

Equation 4.5 has been plotted in Figure 4-2 for the applicable range of flows.

### *4.2.5 Disinfection*

Disinfection is used to kill off pathogenic bacteria prior to a CSO discharge. The best current source of data on disinfection (chlorination without dechlorination) is US EPA (1993). This source relates cost as a function of size, or design flow. This relationship has been updated to 1/99 $ and is expressed in equation 4.6:

$$C = 0.161Q^{0.464} \tag{4-6}$$

Where:

$C$ = construction cost, millions 1/99 $

$Q$ = design flow rate, MGD (where $1 \leq Q \leq 200$ MGD)

Equation 4.6 has been plotted in Figure 4-2 for the applicable range of flows.

### *4.2.6 Best management practices*

The term "Best Management Practices" (BMPs) is used for any practice meant to control and manage the quality or quantity of urban runoff (Urbonas, 1999). This definition delineates stormwater BMPs as structural and nonstructural. Structural BMPs include such devices as detention basins, retention basins, infiltration trenches or basins. They are typically constructed as part of the urban development process to mitigate the deleterious effects of urban runoff. A key BMP, minimizing the directly connected impervious area, is not included in this analysis as very little data is available on its cost (Urbonas, 1999). The more typical, nonstructural BMPs, include such activities as street sweeping and public education on the disposal of pollutants, e.g., oils. These methods are more difficult to assess.

4.2.6.1 Detention basins

Detention basins are storage basins designed to empty after each storm. These basins are most common in rapidly developing urban areas. They use an undersized outlet which causes water to back up and fill the basin (Ferguson, 1998). The rate of discharge depends upon the outlet size and is usually set by local standard. Detention basins attenuate the peak runoff from the developed area. These basins perform well in controlling local water quantity impacts of urban runoff. If the outlet is designed appropriately, water quality can also be controlled to some extent.

The best current source of cost information is Young et al. (1996), which gives cost as a function of storage volume as shown in equation 4.7:

$$C = 55{,}000V^{0.69} \tag{4-7}$$

Where:
$C$ = construction cost, 1/99 $
$V$ = volume of basin, Mgal

The construction costs have been updated to 1/99 $. Land costs were excluded. This relationship is plotted in Figure 4-3. Off-line surface storage for CSO controls is plotted alongside these for comparison purposes. The basis for this relationship is a study done for the Metropolitan Washington Council of Governments (Wiegand et al., 1986).

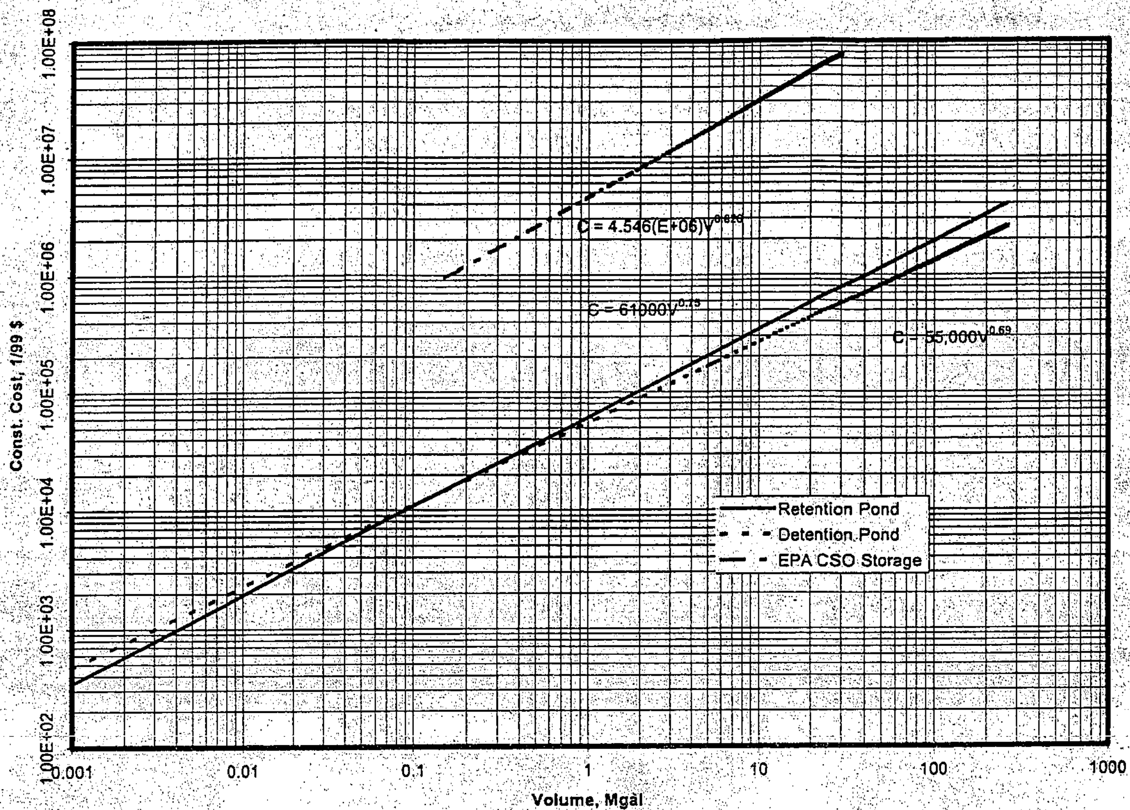



**Figure 4-3. Construction costs of detention, retention, and offline surface units (Adapted from Young et al., 1996).**

4.2.6.2 Retention basins

Retention basins are similar to detention basins, except that the permanent pool is increased. By increasing the permanent pool, (i.e., the point at which discharge occurs), in the storage volume (and typically increasing the storage size as well), increased physical and biological treatment occurs due to the longer residence time in the basin. These types of basins are called retention basins, or wet ponds. The amount of physical storage available is determined by the difference between the height set as the permanent pool volume and the height above the top of the weir or outlet structure available, or freeboard. Because cost depends upon volume, retention basins are more costly in controlling the same amount of peak discharge as a dry detention basin from a quantity standpoint.

The best available cost data on retention basins is found in Young et al. (1996), which gives cost as a function of the total volume of the pond (not the available storage). This relationship is:

$$C = 61{,}000V^{0.75} \tag{4-8}$$

Where:

$C$ = construction cost, 1/99 \$
$V$ = volume of pond, Mgal

The construction costs have been updated to 1/99 \$. Land costs were excluded. This relationship is plotted in Figure 4-3. The basis for this relationship is a study done for the Metropolitan Washington Council of Governments (Wiegand et al., 1986). The data behind this relationship was not reported.

4.2.6.3 Infiltration trenches

Infiltration is the process of runoff water soaking into the ground. Since infiltrated water is removed from surface waters, it represents a complete control for that fraction of stormwater that can be infiltrated (Ferguson, 1998). An infiltration trench is used in areas where space is a problem. It usually consists of excavating a void volume, lining the volume with filter fabric to keep out fine material, installation of conveyance piping, and filling the void with gravel or crushed stone. The trench's performance depends greatly upon the soil characteristics of the area, and operating and maintenance practices (Urbonas, 1999).

The best available cost data on infiltration trenches is found in Young et al. (1996), which gives cost as a function of the total volume of the trench. This relationship is:

$$C = 157V^{0.63} \qquad \textbf{(4-9)}$$

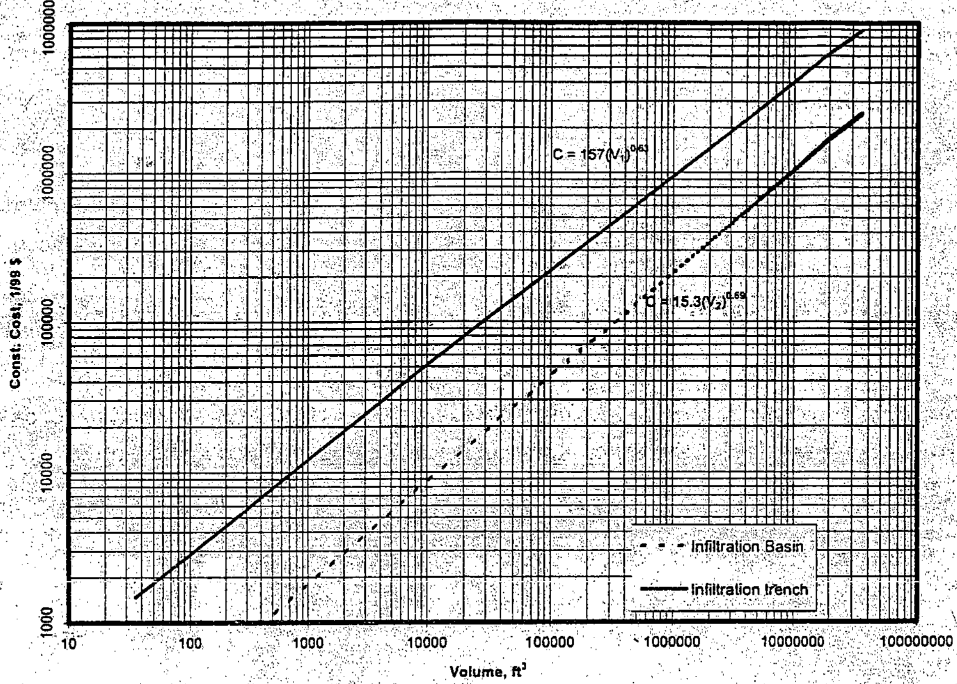
Where:

$C$ = construction cost, 1/99 \$
$V$ = volume of trench, $ft^3$

The source did not list the data for this relationship. The construction costs have been updated to 1/99 \$. Land costs were excluded. This relationship is plotted in Figure 4-4.

4.2.6.4 Infiltration basins

Infiltration basins are similar to retention ponds; however, they are typically used in flatter terrain, and discharge only in low frequency events. Permeable soils underlying the basin and high rates of evapotranspiration are the major prerequisite for using these basins. The water typically can only leave via percolation into the groundwater, or evapotranspiration. Performance in buffering runoff water quality is high; however, from a quantity standpoint, a large land area must be used to control significant runoff events. A major disadvantage is the high maintenance involved due to clogging of the basin.




**Note: $V_1$= trench volume; $V_2$=basin volume**
**Figure 4-4. Construction cost, infiltration trenchs and basins (Adapted from Young et al., 1996).**

The best available cost data on infiltration basins is found in Young et al. (1996), which gives cost as a function of the total volume of the basin. This relationship is:

$$C = 15.3V^{0.69}$$

**(4-10)**

Where:

$C$ = construction cost, 1/99 $
$V$ = volume of infiltration basin, ft$^3$

The construction costs have been updated to 1/99 $. Land costs were excluded. Equation 4.10 is plotted in Figure 4-4. The basis for this relationship is a study done by Schueler (1987). The data that this relationship was based upon were not reported.

4.2.6.5 Sand filters

Sand filters remove sediment and pollutants from runoff. Usually the filters have a presettling chamber to induce settling of the larger solids that would typically clog the sand filter itself. The filtered outflow is collected, rather than infiltrated, and either discharged, or treated further. Performance of these systems is typically good in space-limited areas and in arid climates (Young et al., 1996).

The best available cost data on sand filters is found in Young et al. (1996), which gives cost as a function of the total impervious surface area draining to the filter. This relationship is found in equation 4.11:

$$C = KA \tag{4-11}$$

Where:

$C$ = construction cost, 1/99 \$
$A$ = impervious surface, acres
$K$ = constant, ranging from 11,200 to 22,400

The construction costs have been updated to 1/99 \$. Land costs were excluded. The basis for this relationship is a study done for the Metropolitan Washington Council of Governments (Schueler 1994). The data behind this relationship was not reported.

4.2.6.6 Water quality inlet

Water quality inlets are inlets modified for the control of some solids, oil, and grease. These are sometimes referred to as oil and grit separators. According to Urbonas (1999), the performance of these devices has not been very good.

The best available cost data on water quality inlets is found in Young et al. (1996). Updated to 1/99 \$, the costs range from \$7,200 to \$21,500. The basis for this relationship is a study done by Schueler (1987). The data behind this relationship was not reported.

4.2.6.7 Grassed swales

Grassed swales are vegetated channels used in lieu of the traditional concrete curb and gutter typical of urban areas. Pollutants are removed through filtration by vegetation, settling, and infiltration into the soil (Young et al., 1996). The performance of these systems is highly variable. The use of swales is not recommended in dense urban areas where space is at a premium, or in commercial/industrial areas where contamination of groundwater can occur due to oils and grease in the effluent (Urbonas, 1999).

The best available cost data on grassed swales is found in Young et al. (1996), in which cost is found to vary as follows:

$$C = KL \tag{4-12}$$

Where:

$C$ = construction cost, 1/99 \$
$L$ = length of swale, ft

$K$ = constant, 5 to14

The construction costs have been updated to 1/99 \$. No land costs were included in this analysis. These costs can be significant because an increased right-of-way is needed to include the swale. The basis for this relationship is a study done by Schueler (1992). The data behind this relationship was not reported.

4.2.6.8 Vegetated filter strip

Vegetated filter strips are located adjacent to an impervious surface and gradually sloped to allow overland flow to run slowly across the vegetation. Pollutants are adsorbed and filtered by the vegetated material. High volumes or velocities are not appropriate for these types of areas (Young et al., 1996). Good removal of pollutants can be achieved, assuming the width of the strip is sufficient (Urbonas 1999). No cost information is available, because the designs are highly variable (Young et al., 1996).

4.2.6.9 Wetlands

Wetlands are a modification of the retention pond/infiltration pond to include a broad, shallow, shelf that is inundated periodically under low frequency events. Under these conditions a littoral wetland ecosystem is planted, or allowed to form. The design of wetlands is similar to that of the retention pond, but because of relatively high adsorption surfaces and high levels of biological productivity, wetland pollution removal rates tend to be better (Young et al., 1996). Cost information is not given, as the designs are highly variable (Young et al., 1996)

4.2.6.10 Porous pavements

Porous pavements are a modification to asphalt pavements to allow some infiltration to occur. A berm is used to trap water and contain it on site. Typically, porous pavement infiltration rates are much lower than rates in infiltration basins, although similar treatment characteristics can occur. This method is reserved for low traffic areas because high vehicular traffic can damage the pavement due to "pumping" of groundwater. (Young et al., 1996). Porous pavements can also be negatively affected by freezing temperatures due to frost heave. Cost information is not given, because the designs are highly variable (Young et al., 1996)

4.2.6.11 Nonstructural BMPs

Nonstructural BMPs include such management practices as street sweeping, and educational programs, e.g., on oil recycling. Although important benefits may result from these activities, they are typically difficult to measure, and when measured, usually the constituent measured may have not a causal relationship with a variable that directly affects receiving water quality (Urbonas, 1999). Because of their indirect nature, detailed cost information is not available (Heaney et al., 1998c).

4.2.6.12 Assessment of BMP control performance

An overall assessment of structural BMP control performance can be found in Table 4-1 (Urbonas, 1999). The table lists expected removal ranges for total suspended solids, total phosphorus, total nitrogen, zinc, lead, BOD, and bacteria, compiled from several different sources. Urbonas (1999) however, cautions the use of the table alone, he argues that the definition of "effectiveness is fundamentally flawed, as it is typically a snapshot in time, and ignores the performance of the control over time, and the variability of maintenance to the control." For example, porous pavement is excellent at removal of solids, but is certainly not designed to do so and will clog very quickly if a high solids loading is applied to it.

**Table 4-1. BMP Pollutant Removal Ranges (Urbonas, 1999)**

| Structural BMP | Removal Range (%) | | | | | | |
|---|---|---|---|---|---|---|---|
| | TSS | Total P | TKN | Zinc | Lead | $BOD_5$ | Bacteria |
| Porous Pavement | 80 - 95 | 65 | 75 - 85 | 98 | 80 | 80 | N/A |
| Grass Buffer Strip | 10 - 20 | 0 - 10 | 0 - 10 | 0 - 10 | N/A | N/A | N/A |
| Grass Lined Swale | 20 - 40 | 0 - 15 | 0 - 15 | 0 - 20 | N/A | N/A | N/A |
| Infiltration Basin | 0 - 98 | 0 - 75 | 0 - 70 | 0 - 99 | 0 - 99 | 0 - 90 | 75 - 98 |
| Percolation Trench | 98 | 65 - 75 | 60 - 70 | 95 - 98 | N/A | 90 | 98 |
| Retention Pond | 91 | 0 - 79 | 0 - 80 | 0 - 71 | 9 - 95 | 0 - 69 | N/A |
| Extended Detention | 50 - 70 | 10 - 20 | 10 - 20 | 30 - 60 | 75 - 90 | N/A | 50 - 90 |
| Wetland Basin | 40 - 94 | (-)4 - 90 | 21 | (-)29 - 82 | 27 - 94 | 18 | N/A |
| Sand Filters (fraction flowing through filter) | 14 - 96 | 5 - 92 | (-)129 - 84 | 10 - 98 | 60 - 80 | 60 - 80 | N/A |

Note: The above-reported removal rates represent a variety of site conditions and influent-effluent concentration ranges. It is not appropriate to use the averages of these rates for any of the reported constituents as design objectives for expected BMP performance or for its permit effluent conditions. Keep in mind that influent concentrations, local climate, geology, meteorology and site-specific design details and storm event-specific runoff conditions affect the performance of all BMPs.

Urbonas (1999) advocates a more design-oriented approach in assessing control performance. An example of this approach is found in Table 4-2. While subjective, this approach does provide the designer with enough information to evaluate the control under a wider range of conditions than the regulatory approach found in Table 4.1. However, much more work needs to be done in this area to properly assess the expected benefits of the BMP control in question.

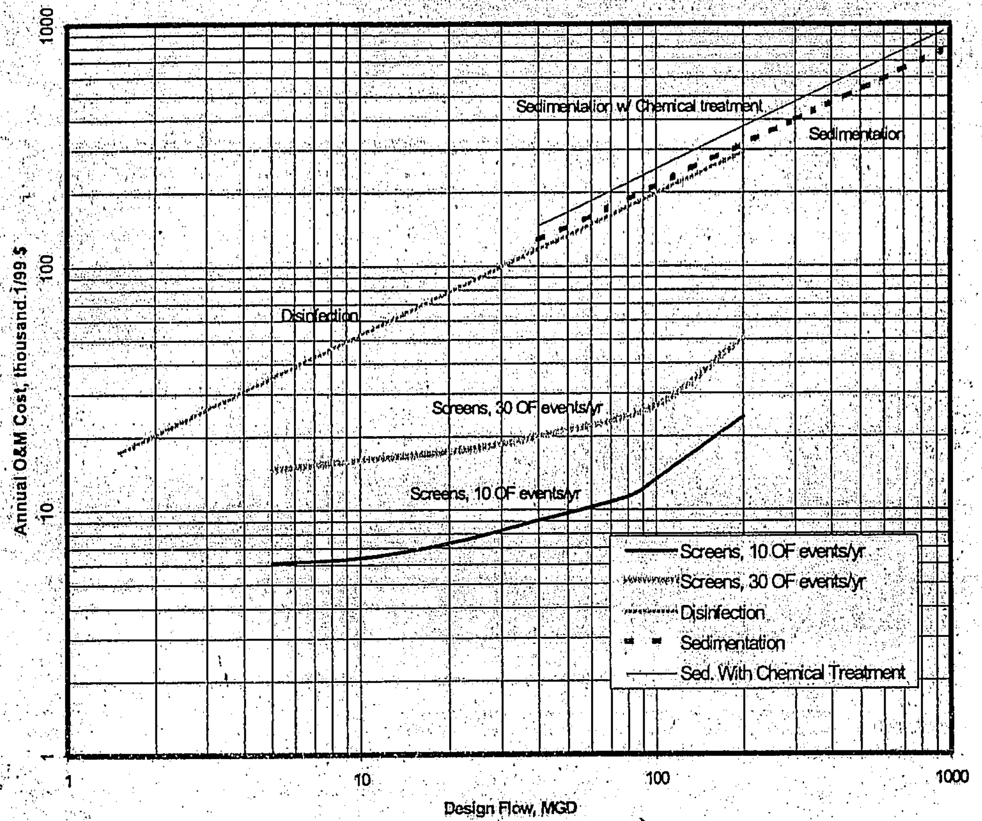
**Table 4-2. An Assessment of Design Robustness Technology for Several BMPs (Urbonas, 1999.)**

| Structural BMP | Hydraulic Design[a] | Removal of Constituents in Stormwater: TSS | Removal of Constituents in Stormwater: Dissolved | Overall Design Robustness |
|---|---|---|---|---|
| Swale | High | Low - Moderate | None - Low | Low |
| Buffer (filter) strip[b] | Low – Moderate | Low - Moderate | None - Low | Low |
| Infiltration basin[c] | Low – High | High | Moderate - High | Low – Moderate |
| Percolation trench | Low – Moderate | High | Moderate - High | Low – Moderate |
| Extended detention (dry) | High | Moderate - High | None - Low | Moderate - High |
| Retention pond (wet) | High | High | Low - Moderate | Moderate - High |
| Wetland | Moderate – High | Moderate - High | Low - Moderate | Moderate |
| Media filter | Low – Moderate | Moderate - High | None - Low | Low – Moderate |
| Oil separator | Low – Moderate | Low | None - Low | Low |
| Catch basin inserts | Uncertain | N/A | N/A | N/A |
| Monolithic porous pavement[b] | Low – Moderate | Moderate - High | Low - High[c] | Low |
| Modular porous pavement[b] | Moderate – High | Moderate - High | Low - High[c] | Low – Moderate |

[a]Weakest design aspect, hydraulic or constituent removal, governs overall design robustness.
[b]Robustness is site-specific and very much maintenance-dependent.
[c]Low-to-Moderate whenever designed with an underdrain and not intended for infiltration;

## 4.3 Operation and Maintenance Costs for Controls

Operation and maintenance cost data for controls are only available for a limited number of CSO-type controls; i.e., sedimentation, disinfection, and screens. CSO-type controls are expected to be significantly more expensive in terms of operating and maintenance costs than those controls that handle only stormwater, however, no data were available (beyond anecdotal) for non CSO-type controls. These relationships can be found in Figure 4-5 from US EPA (1993). For a complete cost/benefit analysis of each control, one needs operating and maintenance costs to complete a life-cycle cost analysis (LCA). LCA is done by bringing all controls to the same design life (by including replacements as necessary), amortizing the control over the same period, and including in this annual cost the annual operating and maintenance cost for each control. LCA is then compared to the benefits of the control.




Note: OF = overflow

**Figure 4-5. Operation and maintenance costs for CSO controls (Adapted from US EPA 1993).**

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# Chapter 5

## Process-Level Cost Estimation

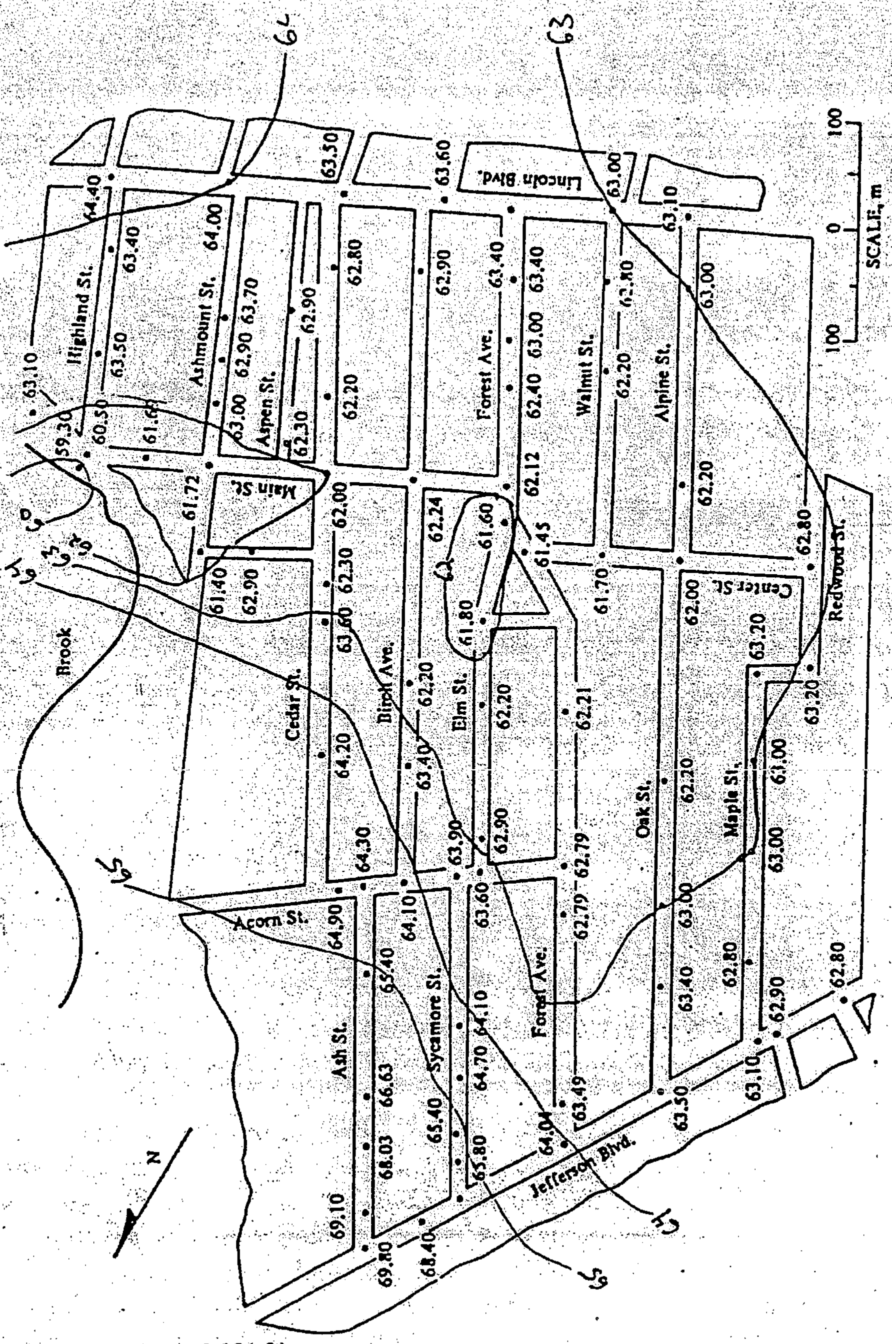
The utility of the cost estimation models presented herein can be illustrated by applying them to a proposed design. By automating the design in a spreadsheet model, many different designs can be evaluated.

### 5.1 Case Study

During the literature review, several urban stormwater design case studies were evaluated to determine if any of them were suitable to demonstrate process-level cost estimation. Tchobanoglous 1981 presents calculations for designing sanitary and storm sewers for the same study area. The total area is approximately 106 acres. The topography of the study area is shown in Figure 5-1. The highest part of the drainage area is on the north side. All drainage ultimately goes to a local brook. The layout of the storm sewer system is shown in Figure 5-2. The entire study area is divided into 54 sub-areas that range in size from 0.8 to 3.4 acres in size. A spreadsheet was designed to incorporate all of the necessary information for design by trial and error. The calculations are presented in tables 5.1, 5.2 and 5.3, which are described below.

#### *5.1.1 Calculate the design flows into the drainage system*

Table 5-1 consists of 69 rows and 20 columns. Each row designates a link in the drainage network. The land use for the total area is shown in Figure 5-3. Total land use consists of the mix of uses shown in Table 5-2. The dwelling units/acre for each link is listed in column 7 of Table 5-1 (except for commercial and schools, which are listed as –1 and –2, respectively). The percent imperviousness is related to land use as shown in Table 5-3. Two cases will be considered: existing zoning practices, and low impact development (LID) land use practices. If LID is used, the imperviousness for all land uses is assumed reduced by 30%. Column 8 of Table 5-1 is then computed, listing the impervious percentage for each link. Column 9 of Table 5-1 is the multiplication of the drainage area in acres from column 6 times the impervious percentage of column 8. Column 10 of Table 5-1 is the impervious coefficient of the impervious area, nominally 1.0. Column 12 of Table 5-1 is the impervious area, or column 9, totaled within each branch. Column 13 is the permeable area within the link, or the total area minus the impervious area. Based upon the land use, through a lookup table, a runoff coefficient is assigned in column 14. A cumulative runoff coefficient is calculated in column 15. Column 16 is computed by assuming an initial flow time of 20 min, and summing the previous link in the branch's time in column 17. Column 17 is calculated by dividing the distance in column 5 by the Manning velocity for the design pipe diameter. Column 18 is the sum of columns 17 and 16. Column 19 is the rainfall intensity for the given time in column 18. Column 20 is computed by the Rational Method, to be explained later.




(elevations in meters; 1 m = 3.281 ft)
Figure 5-1. Study area topography (Adopted from Tchobanoglous, 1981). (Reproduced with permission of The McGraw-Hill Companies).

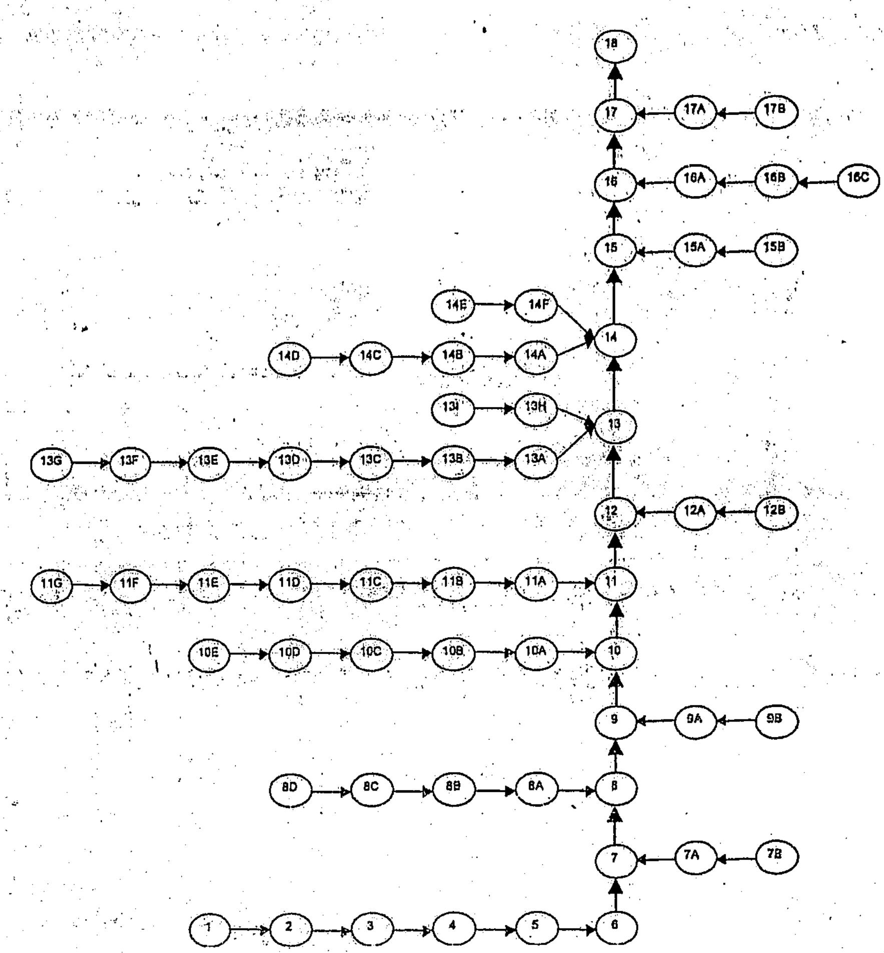



**Figure 5-2. Study area sewer network.**

# Table 5-1. Sewer Network Design Hydrology

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Street | Type | Nodes From | Nodes To | Sewer Length (ft) | Drainage Area (ac) | Dwelling Units/ acre | Percent Impervious | Impervious Area, IA (ac) | IA Runoff Coeff. | Cumulative Total (ac) | Cumulative Impervious (ac) | Pervious Area, PA (ac) | PA Runoff Coeff. | Cumulative Runoff Coeff. | Flow Time (min) To Upper End | Flow Time (min) In Section | Flow Time (min) Total Time | Rain Intensity (in/hr) | Peak Discharge (ac-in/hr) |
| Maple/Redwood | Branch | 1 | 2 | 279 | 2.30 | 2 | 35 | 0.80 | 1.00 | 2.30 | 0.80 | 1.49 | 0.30 | 0.55 | 20.00 | 2.32 | 22.32 | | |
| Maple/Redwood | Branch | 2 | 3 | 299 | 2.40 | 2 | 35 | 0.84 | 1.00 | 4.70 | 1.64 | 1.56 | 0.30 | 0.55 | 22.32 | 1.21 | 23.54 | 2.49 | 6.38 |
| Maple/Redwood | Branch | 3 | 4 | 272 | 2.20 | 2 | 35 | 0.77 | 1.00 | 6.89 | 2.41 | 1.43 | 0.30 | 0.55 | 23.54 | 1.15 | 24.69 | 2.41 | 9.07 |
| Maple/Redwood | Branch | 4 | 5 | 148 | 1.51 | 2 | 35 | 0.53 | 1.00 | 8.40 | 2.94 | 0.98 | 0.30 | 0.55 | 24.69 | 0.54 | 25.23 | 2.38 | 10.90 |
| Maple/Redwood | Branch | 5 | 6 | 325 | 2.20 | 2 | 35 | 0.77 | 1.00 | 10.60 | 3.71 | 1.43 | 0.30 | 0.55 | 25.23 | 1.26 | 26.49 | 2.31 | 13.35 |
| Alpine | Branch | 7B | 7A | 367 | 3.41 | 10 | 56 | 1.91 | 1.00 | 3.41 | 1.91 | 1.50 | 0.30 | 0.69 | 20.00 | 3.06 | 23.06 | | |
| Alpine | Branch | 7A | 7 | 367 | 2.59 | 10 | 56 | 1.45 | 1.00 | 6.00 | 3.36 | 1.14 | 0.30 | 0.69 | 23.06 | 1.35 | 24.41 | 2.43 | 10.10 |
| Oak | Branch | 8D | 8C | 328 | 2.50 | 3 | 40 | 1.00 | 1.00 | 2.50 | 1.00 | 1.50 | 0.30 | 0.58 | 20.00 | 2.73 | 22.73 | | |
| Oak | Branch | 8C | 8B | 328 | 2.40 | 3 | 40 | 0.96 | 1.00 | 4.89 | 1.96 | 1.44 | 0.30 | 0.58 | 22.73 | 0.67 | 23.40 | 2.49 | 7.06 |
| Oak | Branch | 8B | 8A | 328 | 2.50 | 3 | 40 | 1.00 | 1.00 | 7.39 | 2.96 | 1.50 | 0.30 | 0.58 | 23.40 | 1.08 | 24.48 | 2.43 | 10.40 |
| Oak | Branch | 8A | 8 | 328 | 2.79 | 3 | 40 | 1.12 | 1.00 | 10.18 | 4.07 | 1.68 | 0.30 | 0.58 | 24.48 | 0.99 | 25.46 | 2.37 | 13.98 |
| Walnut | Branch | 9B | 9A | 394 | 2.69 | -2 | 35 | 0.94 | 1.00 | 2.69 | 0.94 | 1.75 | 0.30 | 0.55 | 20.00 | 3.28 | 23.28 | | |
| Walnut | Branch | 9A | 9 | 394 | 2.99 | -2 | 35 | 1.05 | 1.00 | 5.68 | 1.99 | 1.94 | 0.30 | 0.55 | 23.28 | 1.29 | 24.57 | 2.42 | 7.50 |
| W. Forest | Branch | 10E | 10D | 394 | 2.89 | 5 | 46 | 1.33 | 1.00 | 2.89 | 1.33 | 1.56 | 0.30 | 0.62 | 20.00 | 3.28 | 23.28 | | |
| W. Forest | Branch | 10D | 10C | 344 | 2.50 | 5 | 46 | 1.15 | 1.00 | 5.39 | 2.48 | 1.35 | 0.30 | 0.62 | 23.28 | 1.13 | 24.41 | 2.43 | 8.14 |
| W. Forest | Branch | 10C | 10B | 328 | 3.09 | 5 | 46 | 1.42 | 1.00 | 8.48 | 3.90 | 1.67 | 0.30 | 0.62 | 24.41 | 0.98 | 25.39 | 2.37 | 12.51 |
| W. Forest | Branch | 10B | 10A | 328 | 2.40 | 5 | 46 | 1.10 | 1.00 | 10.87 | 5.00 | 1.29 | 0.30 | 0.62 | 25.39 | 0.99 | 26.38 | 2.32 | 15.67 |
| W. Forest | Branch | 10A | 10 | 246 | 0.99 | 5 | 46 | 0.45 | 1.00 | 11.86 | 5.46 | 0.53 | 0.30 | 0.62 | 26.38 | 0.74 | 27.12 | 2.28 | 16.81 |
| E. Forest | Branch | 12B | 12A | 328 | 1.80 | 12 | 60 | 1.08 | 1.00 | 1.80 | 1.08 | 0.72 | 0.30 | 0.72 | 20.00 | 2.73 | 22.73 | | |
| E. Forest | Branch | 12A | 12 | 328 | 2.20 | 12 | 60 | 1.32 | 1.00 | 4.00 | 2.40 | 0.88 | 0.30 | 0.72 | 22.73 | 0.84 | 23.58 | 2.48 | 7.16 |
| Sycamore/Elm | Branch | 11G | 11F | 328 | 2.10 | 5 | 46 | 0.97 | 1.00 | 2.10 | 0.97 | 1.13 | 0.50 | 0.73 | 20.00 | 2.73 | 22.73 | | |
| Sycamore/Elm | Branch | 11F | 11E | 279 | 2.10 | 5 | 46 | 0.97 | 1.00 | 4.20 | 1.93 | 1.13 | 0.50 | 0.73 | 22.73 | 0.72 | 23.45 | 2.49 | 7.64 |
| Sycamore/Elm | Branch | 11E | 11D | 262 | 2.20 | 5 | 46 | 1.01 | 1.00 | 6.40 | 2.94 | 1.19 | 0.50 | 0.73 | 23.45 | 0.86 | 24.31 | 2.44 | 11.38 |
| Sycamore/Elm | Branch | 11D | 11C | 82 | 0.00 | 5 | 46 | 0.00 | 1.00 | 6.40 | 2.94 | 0.00 | 0.50 | 0.73 | 24.31 | 0.32 | 24.63 | 2.42 | 11.29 |
| Sycamore/Elm | Branch | 11C | 11B | 328 | 1.61 | 5 | 46 | 0.74 | 1.00 | 8.01 | 3.68 | 0.87 | 0.50 | 0.73 | 24.63 | 0.59 | 25.22 | 2.38 | 13.92 |
| Sycamore/Elm | Branch | 11B | 11A | 328 | 1.71 | 5 | 46 | 0.78 | 1.00 | 9.71 | 4.47 | 0.92 | 0.30 | 0.71 | 25.22 | 0.99 | 26.21 | 2.33 | 16.07 |
| Sycamore/Elm | Branch | 11A | 11 | 295 | 1.41 | 5 | 46 | 0.65 | 1.00 | 11.12 | 5.12 | 0.76 | 0.30 | 0.70 | 26.21 | 1.06 | 27.26 | 2.27 | 17.67 |
| Ash/Acorn/Birch | Branch | 13G | 13F | 328 | 1.71 | 5 | 46 | 0.78 | 1.00 | 1.71 | 0.78 | 0.92 | 0.50 | 0.73 | 20.00 | 2.73 | 22.73 | | |
| Ash/Acorn/Birch | Branch | 13F | 13E | 328 | 2.50 | 5 | 46 | 1.15 | 1.00 | 4.20 | 1.93 | 1.35 | 0.50 | 0.73 | 22.73 | 0.64 | 23.37 | 2.50 | 7.65 |
| Ash/Acorn/Birch | Branch | 13E | 13D | 328 | 1.80 | 5 | 46 | 0.83 | 1.00 | 6.00 | 2.76 | 0.97 | 0.50 | 0.73 | 23.37 | 0.64 | 24.01 | 2.46 | 10.76 |
| Ash/Acorn/Birch | Branch | 13D | 13C | 82 | 0.82 | 5 | 46 | 0.38 | 1.00 | 6.82 | 3.14 | 0.44 | 0.50 | 0.73 | 24.01 | 0.27 | 24.28 | 2.44 | 12.14 |
| Ash/Acorn/Birch | Branch | 13C | 13B | 394 | 2.00 | 5 | 46 | 0.92 | 1.00 | 8.82 | 4.06 | 1.08 | 0.50 | 0.73 | 24.28 | 1.02 | 25.30 | 2.38 | 15.31 |
| Ash/Acorn/Birch | Branch | 13B | 13A | 394 | 2.20 | 5 | 46 | 1.01 | 1.00 | 11.02 | 5.07 | 1.19 | 0.30 | 0.71 | 25.30 | 0.84 | 26.14 | 2.33 | 18.20 |
| Ash/Acorn/Birch | Branch | 13A | 13 | 394 | 1.90 | 5 | 46 | 0.88 | 1.00 | 12.92 | 5.94 | 1.03 | 0.30 | 0.70 | 26.14 | 1.00 | 27.14 | 2.28 | 20.48 |
| East Birch | Branch | 13I | 13H | 262 | 2.00 | -1 | 80 | 1.60 | 1.00 | 2.00 | 1.60 | 0.40 | 0.30 | 0.86 | 20.00 | 2.18 | 22.18 | | |
| East Birch | Branch | 13H | 13 | 262 | 2.30 | -1 | 80 | 1.84 | 1.00 | 4.30 | 3.44 | 0.46 | 0.30 | 0.86 | 22.18 | 0.96 | 23.15 | 2.51 | 9.29 |
| W. Cedar | Branch | 14D | 14C | 262 | 2.00 | 5 | 46 | 0.92 | 1.00 | 2.00 | 0.92 | 1.08 | 0.50 | 0.73 | 20.00 | 2.19 | 22.19 | | |
| W. Cedar | Branch | 14C | 14B | 262 | 2.50 | 5 | 46 | 1.15 | 1.00 | 4.50 | 2.07 | 1.35 | 0.50 | 0.73 | 22.19 | 0.87 | 23.06 | 2.52 | 8.26 |
| W. Cedar | Branch | 14B | 14A | 262 | 2.20 | 5 | 46 | 1.01 | 1.00 | 6.70 | 3.08 | 1.19 | 0.50 | 0.73 | 23.06 | 0.48 | 23.54 | 2.49 | 12.15 |
| W. Cedar | Branch | 14A | 14 | 262 | 1.31 | 5 | 46 | 0.60 | 1.00 | 8.01 | 3.68 | 0.71 | 0.50 | 0.73 | 23.54 | 0.73 | 24.26 | 2.44 | 14.26 |
| E. Cedar | Branch | 14E | 14F | 262 | 1.11 | -1 | 80 | 0.89 | 1.00 | 1.11 | 0.89 | 0.22 | 0.50 | 0.90 | 20.00 | 2.19 | 22.19 | | |
| E. Cedar | Branch | 14F | 14 | 262 | 1.61 | -1 | 80 | 1.28 | 1.00 | 2.72 | 2.17 | 0.32 | 0.50 | 0.90 | 22.19 | 0.81 | 22.99 | 2.52 | 6.17 |
| Aspen | Branch | 15B | 15A | 328 | 1.26 | -1 | 80 | 1.01 | 1.00 | 1.26 | 1.01 | 0.25 | 0.50 | 0.90 | 20.00 | 2.73 | 22.73 | | |
| Aspen | Branch | 15A | 15 | 262 | 2.05 | -1 | 80 | 1.64 | 1.00 | 3.31 | 2.65 | 0.41 | 0.50 | 0.90 | 22.73 | 0.71 | 23.44 | 2.49 | 7.42 |
| W. Ashmont | Branch | 16C | 16B | 328 | 3.51 | 5 | 46 | 1.61 | 1.00 | 3.51 | 1.61 | 1.89 | 0.70 | 0.84 | 20.00 | 2.73 | 22.73 | | |
| W. Ashmont | Branch | 16B | 16A | 328 | 2.20 | 5 | 46 | 1.01 | 1.00 | 5.71 | 2.63 | 1.19 | 0.70 | 0.84 | 22.73 | 0.80 | 23.54 | 2.49 | 11.69 |
| W. Ashmont | Branch | 16A | 16 | 246 | 2.10 | 5 | 46 | 0.97 | 1.00 | 7.81 | 3.59 | 1.13 | 0.70 | 0.84 | 23.54 | 0.60 | 24.14 | 2.45 | 16.01 |
| E. Ashmont | Branch | 16E | 16D | 262 | 2.20 | -1 | 80 | 1.76 | 1.00 | 2.20 | 1.76 | 0.44 | 0.70 | 0.94 | 20.00 | 2.19 | 22.19 | | |
| E. Ashmont | Branch | 16D | 16 | 246 | 1.80 | -1 | 80 | 1.44 | 1.00 | 4.00 | 3.20 | 0.36 | 0.70 | 0.94 | 22.19 | 0.48 | 22.67 | 2.54 | 9.56 |
| Highland | Branch | 17B | 17A | 262 | 2.10 | -1 | 80 | 1.68 | 1.00 | 2.10 | 1.68 | 0.42 | 0.70 | 0.94 | 20.00 | 2.18 | 22.18 | | |
| Highland | Branch | 17A | 17 | 246 | 2.00 | -1 | 80 | 1.60 | 1.00 | 4.10 | 3.28 | 0.40 | 0.70 | 0.94 | 22.18 | 0.22 | 22.41 | 2.56 | 9.87 |
| Maple/Redwood | Trunk | 6 | 7 | 400 | 10.60 | 2 | 35 | 3.71 | 1.00 | 10.60 | 3.71 | 6.89 | 0.30 | 0.55 | 20.00 | 3.34 | 23.34 | 2.50 | 14.43 |
| Alpine | Trunk | 7 | 8 | 36 | 6.00 | 2 | 35 | 2.10 | 1.00 | 16.61 | 5.81 | 3.90 | 0.30 | 0.55 | 23.34 | 0.72 | 24.05 | 2.45 | 22.19 |
| Oak | Trunk | 8 | 9 | 220 | 10.18 | 2 | 35 | 3.56 | 1.00 | 26.79 | 9.38 | 6.62 | 0.30 | 0.55 | 24.05 | 0.06 | 24.12 | 2.45 | 35.74 |
| Walnut | Trunk | 9 | 10 | 230 | 5.68 | 2 | 35 | 1.99 | 1.00 | 32.47 | 11.36 | 3.69 | 0.30 | 0.55 | 24.12 | 0.31 | 24.43 | 2.43 | 42.09 |
| Forest | Trunk | 10 | 11 | 112 | 15.86 | 2 | 35 | 5.55 | 1.00 | 48.33 | 16.92 | 10.31 | 0.30 | 0.55 | 24.43 | 0.37 | 24.80 | 2.41 | 63.40 |
| Elm | Trunk | 11 | 12 | 95 | 11.12 | 2 | 35 | 3.89 | 1.00 | 59.45 | 20.81 | 7.23 | 0.30 | 0.55 | 24.80 | 0.20 | 25.01 | 2.39 | 77.59 |
| Birch | Trunk | 13 | 14 | 246 | 18.83 | 2 | 35 | 6.59 | 1.00 | 94.15 | 32.95 | 12.24 | 0.50 | 0.59 | 25.19 | 0.53 | 25.72 | 2.35 | 131.39 |
| Cedar | Trunk | 14 | 15 | 144 | 9.27 | 2 | 35 | 3.24 | 1.00 | 103.41 | 36.20 | 6.02 | 0.50 | 0.60 | 25.72 | 0.40 | 26.12 | 2.33 | 144.73 |
| Aspen | Trunk | 15 | 16 | 203 | 3.31 | 2 | 35 | 1.16 | 1.00 | 106.72 | 37.35 | 2.15 | 0.50 | 0.60 | 26.12 | 0.26 | 26.38 | 2.32 | 149.02 |
| Ashmont | Trunk | 16 | 17 | 361 | 11.81 | 2 | 35 | 4.13 | 1.00 | 118.53 | 41.49 | 7.68 | 0.50 | 0.61 | 26.38 | 0.37 | 26.75 | 2.30 | 166.06 |
| Highland | Trunk | 17 | 18 | 164 | 4.10 | 2 | 35 | 1.44 | 1.00 | 122.63 | 42.92 | 2.67 | 0.70 | 0.62 | 26.75 | 0.66 | 27.41 | 2.26 | 171.06 |

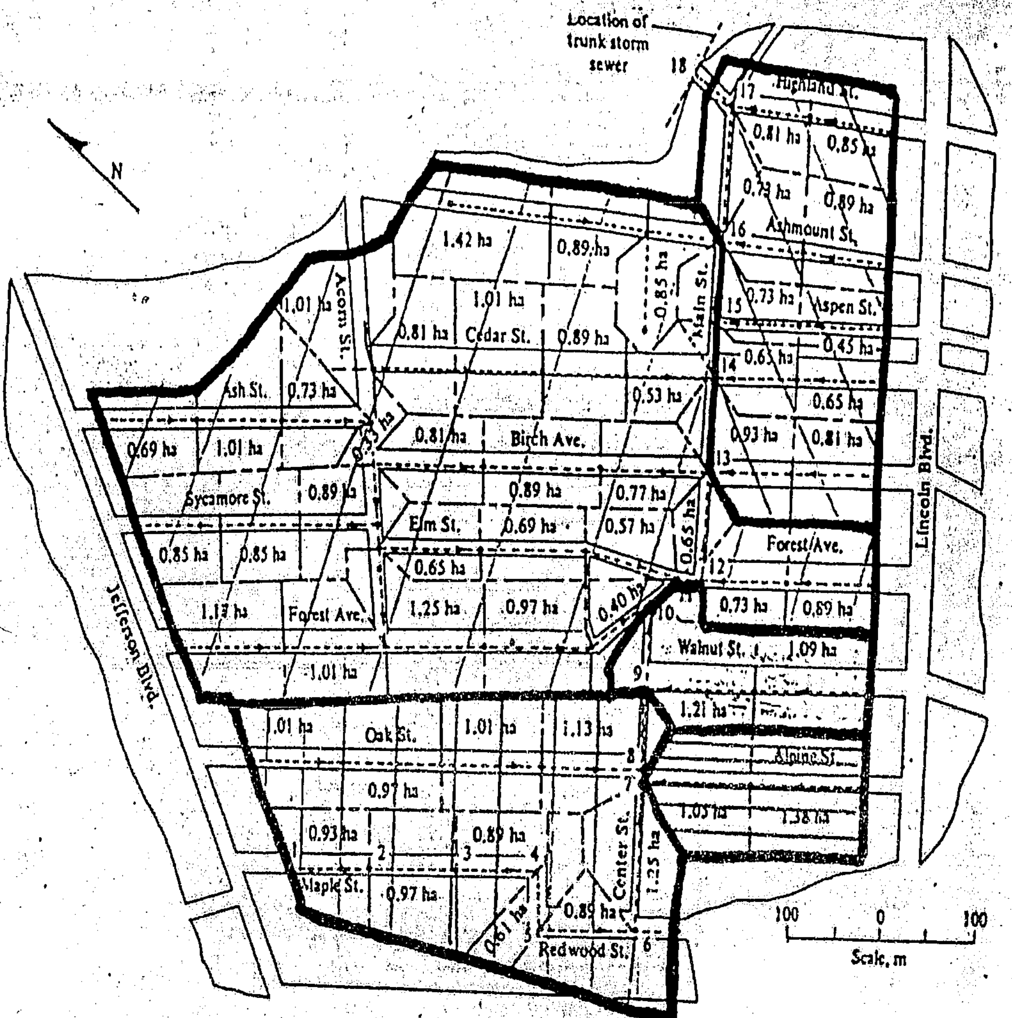



Figure 5-3. Study area land use (Adapted from Tchobanoglous, 1981).
(Reproduced with permission of The McGraw-Hill Companies).

**Table 5-2. Mix of Land Uses in Happy Acres**

| Land Use | Area (acres) | Dwelling Density (units/acre) |
|---|---|---|
| Residential, low density | 20.8 | 2 - 3 |
| Residential, medium density | 51.7 | 5 |
| Apartments | 10.0 | 10 |
| School | 5.7 | N/A |
| Commercial | 18.4 | N/A |
| Total | 106.6 | |

**Table 5-3. Imperviousness for Various Land Uses (Heaney et al., 1998d.)**

| Dwelling (units/acre) | Imperviousness (%) |
|---|---|
| 1 | 30 |
| 2 | 35 |
| 3 | 40 |
| 4 | 43 |
| 5 | 46 |
| 6 | 48 |
| 7 | 50 |
| 8 | 52 |
| 9 | 54 |
| 10 | 56 |
| 11 | 58 |
| 12 | 60 |
| Commercial | 80 |
| School | 35 |

The runoff coefficients for impervious and permeable areas are shown in Table 5-4. Runoff coefficients for permeable areas depend on the soil type.

The expected peak runoff is calculated using the Rational Method, or

$$Q = CiA \qquad \textbf{(5-1)}$$

Where
$Q$ = estimated peak flow, $ft^3/s$
$C$ = runoff coefficient
$i$ = rainfall intensity, in./hr
$A$ = contributing drainage area, acres

**Table 5-4. Runoff Coefficients for Various Areas**

| Description | Runoff Coefficient |
|---|---|
| Directly connected impervious area | 1 |
| Other impervious area | 0.7 |
| Pervious areas Soil Type: | |
| Sand | 0.2 |
| Silt | 0.3 |
| Clay | 0.5 |
| Rock | 0.7 |

The runoff coefficient is calculated in Table 5-1 as the weighted average of the runoff coefficients from the impervious and permeable areas. The total drainage area is calculated by summing the contributing drainage areas. The design rainfall intensity is established by calculating the time of concentration of the runoff. The time of concentration is:

$$t_c = t_i + t_p \tag{5-2}$$

where

$t_c$ = time of concentration, min
$t_i$ = time to inlet, min
$t_p$ = time in pipe, min

The flow time in the pipe is simply

$$t_p = L/v \tag{5-3}$$

where

$L$ = length of pipe, ft
$v$ = velocity, ft/s

However, it is less clear how to estimate the inlet time. For urban areas, inlet times from 5–20 min are used. Following the Tchobanoglous, 1981 protocol, 20 min is used here as the inlet time.

Intensity-duration-frequency (IDF) curves for Boulder, CO and Houston, TX are shown in Figures 5-4 and 5-5 (Bedient and Huber, 1989). A summary of the values of intensity for 20 min in duration for Boulder, CO and Houston, TX is presented in Table 5-5.

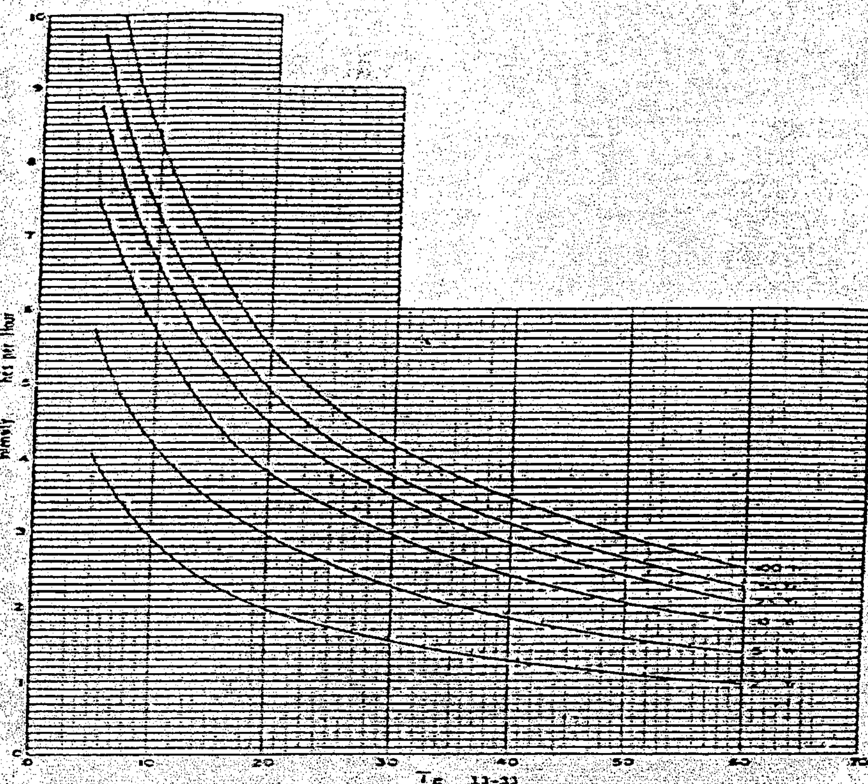



Figure 5-4. Intensity-duration-frequency curves for Boulder, CO (From US SCS, 1973).

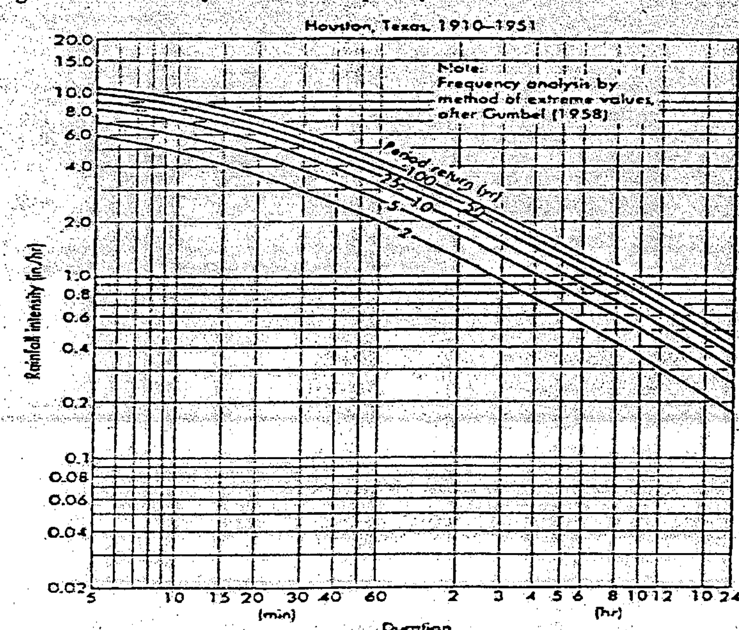



Figure 5-5. Intensity-duration-frequency curves for Houston, TX (Bedient and Huber 1989). (Reprinted by permission of Pearson Education, Inc. Upper Saddle River, New Jersey).

**Table 5-5. Comparison of Design Rainfall Intensities for 20-min Duration Storms in Boulder, CO, and Houston, TX**

| Recurrence Interval (yrs) | Boulder, CO (in./hr) | Houston, TX (in./hr) |
|---|---|---|
| 2 | 2 | 3.6 |
| 5 | 2.9 | 4.7 |
| 10 | 3.9 | 5.6 |
| 25 | 4.5 | 6.1 |
| 50 | 4.9 | 6.8 |
| 100 | 5.5 | 7.3 |

These two cities will be used for the cost analysis as representing a wet area with annual precipitation greater than 40 in. and a semi-arid area with annual precipitation of less than 20 in.

A plot of the intensities vs. recurrence intervals is shown in Figure 5-6. Several observations can be made. First, intensities are about 1.8× larger in Houston, TX than in Boulder, CO. Second, the design intensities increase at a decreasing rate as the recurrence intervals increase. Urban storm drainage designs are usually sized to handle a 5-yr or 10- yr storm. Flood control systems are typically designed to provide protection for the 100-yr storm. For this example, a 5-yr recurrence interval will be used for the initial calculations.. The design recurrence interval can then be varied to see its effect on total cost.

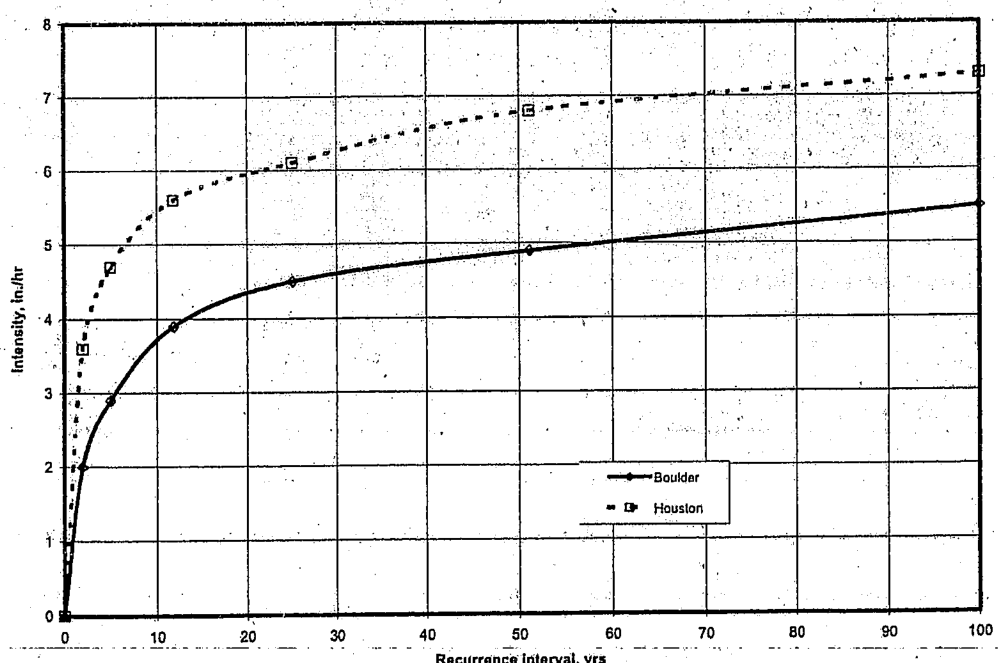



**Figure 5-6. Intensities vs. recurrence interval for Boulder, CO and Houston, TX for a 20-min duration.**

Intensity-Duration-Frequency (IDF) curves can be approximated by equations of the form:

$$i = kt^b \tag{5-4}$$

where

$i$ = rainfall intensity, in./hr
$t$ = time of concentration, min
$k$, $b$ = parameters

The parameters of the IDF equation can be determined by forcing the curve through two points. Using Boulder, CO as an example, intensities for durations of 10 min and 60 min were estimated from the IDF graphs for various recurrence intervals. These estimates of two data points yield the necessary two equations and two unknowns. The two parameters can be calculated using:

$$b = \frac{\ln\left(\frac{i_1}{i_2}\right)}{\ln\left(\frac{t_1}{t_2}\right)} \tag{5-5}$$

$$k = \frac{i_1}{t_1} \tag{5-6}$$

Values of $k$ and $b$ for Boulder, CO are shown in Table 5-6.

**Table 5-6. IDF Curve Parameters for Boulder, CO**

| Recurrence Interval (yrs) | *k* | *b* |
|---|---|---|
| 2 | 12.169 | −0.6228 |
| 5 | 17.234 | −0.6131 |
| 10 | 25.072 | −0.6433 |
| 25 | 29.655 | −0.6526 |
| 50 | 33.127 | −0.6569 |
| 100 | 38.796 | −0.6697 |

Using approximating equations allows the design intensity to be easily recalculated as the time of concentration changes.

The estimated peak flow rates using the Rational Method are shown in the last column of Table 5-1. A much better way to estimate peak flows is to use real storm hydrographs and route these hydrographs through the drainage system using a simulator such as the Stormwater Management Model (SWMM) developed by the US EPA. However, this example will use the "standard practice" of the simpler Rational Method approach.

## Table 5-7. Sewer Network Design Hydraulics

| 1 | 2 | 3 | 4 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Street | Type | Nodes From | To | Trial Slope ID # | Trial Slope (ft/ft) | Trial Pipe ID # | Trial Pipe Dia. (in) | Diameter Check Dia? (2 = OK) | Upstream Depth to top of pipe (ft) | Downstream Depth to top of pipe (ft) | Minimum Cover Check (2=OK) | $Q_f$ (cfs) | Required Q (cfs) | Capacity Check $Q_f$>=Q? (2 = OK) | $Q/Q_f$ | $V/V_f$ | Full Velocity $V_f$ (ft/sec) | Design Velocity V (ft/sec) | Velocity Check 10>V≥3 (2 = good) |
| Maple/Redwood | Branch | 1 | 2 | | | | | | | | | | | | | | | | |
| Maple/Redwood | Branch | 2 | 3 | 4 | 0.004 | 3 | 18 | 2 | 4.0 | 5.2 | 2 | 7.24 | 6.36 | 2 | 0.88 | 1.02 | 4.10 | 4.19 | 2 |
| Maple/Redwood | Branch | 3 | 4 | 3 | 0.003 | 4 | 21 | 2 | 4.9 | 6.4 | 2 | 9.46 | 9.07 | 2 | 0.96 | 1.02 | 3.93 | 4.02 | 2 |
| Maple/Redwood | Branch | 4 | 5 | 4 | 0.004 | 4 | 21 | 2 | 6.4 | 7.0 | 2 | 10.92 | 10.90 | 2 | 1.00 | 1.00 | 4.54 | 4.56 | 2 |
| Maple/Redwood | Branch | 5 | 6 | 3 | 0.003 | 5 | 24 | 2 | 6.8 | 7.7 | 2 | 13.50 | 13.35 | 2 | 0.99 | 1.01 | 4.30 | 4.35 | 2 |
| Alpine | Branch | 7B | 7A | | | | | | | | | | | | | | | | |
| Alpine | Branch | 7A | 7 | 4 | 0.004 | 4 | 21 | 2 | 4.0 | 5.5 | 2 | 10.92 | 10.10 | 2 | 0.92 | 1.03 | 4.54 | 4.66 | 2 |
| Oak | Branch | 8D | 8C | | | | | | | | | | | | | | | | |
| Oak | Branch | 8C | 8B | 13 | 0.013 | 4 | 21 | 2 | 4.0 | 4.3 | 2 | 19.69 | 7.08 | 2 | 0.36 | 0.80 | 8.19 | 6.54 | 2 |
| Oak | Branch | 8B | 8A | 5 | 0.005 | 4 | 21 | 2 | 4.3 | 5.6 | 2 | 12.21 | 10.40 | 2 | 0.85 | 1.02 | 5.08 | 5.17 | 2 |
| Oak | Branch | 8A | 8 | 5 | 0.005 | 5 | 24 | 2 | 5.4 | 6.7 | 2 | 17.43 | 13.98 | 2 | 0.80 | 1.01 | 5.55 | 5.59 | 2 |
| Walnut | Branch | 9B | 9A | | | | | | | | | | | | | | | | |
| Walnut | Branch | 9A | 9 | 5 | 0.005 | 4 | 21 | 2 | 4.0 | 4.3 | 2 | 12.21 | 7.50 | 2 | 0.61 | 0.94 | 5.08 | 4.77 | 2 |
| W. Forest | Branch | 10E | 10D | | | | | | | | | | | | | | | | |
| W. Forest | Branch | 10D | 10C | 5 | 0.005 | 4 | 21 | 2 | 4.0 | 4.4 | 2 | 12.21 | 8.14 | 2 | 0.67 | 0.96 | 5.08 | 4.90 | 2 |
| W. Forest | Branch | 10C | 10B | 6 | 0.006 | 4 | 21 | 2 | 4.4 | 4.4 | 2 | 13.38 | 12.51 | 2 | 0.93 | 1.03 | 5.56 | 5.70 | 2 |
| W. Forest | Branch | 10B | 10A | 5 | 0.005 | 5 | 24 | 2 | 4.2 | 5.1 | 2 | 17.43 | 15.67 | 2 | 0.90 | 1.02 | 5.55 | 5.68 | 2 |
| W. Forest | Branch | 10A | 10 | 5 | 0.005 | 5 | 24 | 2 | 5.1 | 4.4 | 2 | 17.43 | 16.81 | 2 | 0.96 | 1.02 | 5.55 | 5.67 | 2 |
| E. Forest | Branch | 12B | 12A | | | | | | | | | | | | | | | | |
| E. Forest | Branch | 12A | 12 | 10 | 0.01 | 3 | 18 | 2 | 4.0 | 4.3 | 2 | 11.45 | 7.18 | 2 | 0.63 | 0.95 | 6.48 | 6.14 | 2 |
| Sycamore/Elm | Branch | 11G | 11F | | | | | | | | | | | | | | | | |
| Sycamore/Elm | Branch | 11F | 11E | 10 | 0.01 | 3 | 18 | 2 | 4.0 | 4.5 | 2 | 11.45 | 7.64 | 2 | 0.67 | 0.96 | 6.48 | 6.25 | 2 |
| Sycamore/Elm | Branch | 11E | 11D | 5 | 0.005 | 4 | 21 | 2 | 4.2 | 5.2 | 2 | 12.21 | 11.38 | 2 | 0.93 | 1.03 | 5.08 | 5.21 | 2 |
| Sycamore/Elm | Branch | 11D | 11C | 3 | 0.003 | 5 | 24 | 2 | 5.0 | 4.2 | 2 | 13.50 | 11.29 | 2 | 0.84 | 1.02 | 4.30 | 4.37 | 2 |
| Sycamore/Elm | Branch | 11C | 11B | 14 | 0.014 | 5 | 24 | 2 | 4.2 | 4.2 | 2 | 29.17 | 13.92 | 2 | 0.48 | 0.87 | 9.29 | 8.11 | 2 |
| Sycamore/Elm | Branch | 11B | 11A | 5 | 0.005 | 5 | 24 | 2 | 4.2 | 4.6 | 2 | 17.43 | 16.07 | 2 | 0.92 | 1.03 | 5.55 | 5.69 | 2 |
| Sycamore/Elm | Branch | 11A | 11 | 3 | 0.003 | 6 | 27 | 2 | 4.3 | 4.5 | 2 | 18.49 | 17.67 | 2 | 0.96 | 1.02 | 4.65 | 4.76 | 2 |
| Ash/Acorn/Birch | Branch | 13G | 13F | | | | | | | | | | | | | | | | |
| Ash/Acorn/Birch | Branch | 13F | 13E | 18 | 0.0175 | 3 | 18 | 2 | 4.0 | 4.5 | 2 | 15.14 | 7.65 | 2 | 0.51 | 0.89 | 8.57 | 7.61 | 2 |
| Ash/Acorn/Birch | Branch | 13E | 13D | 18 | 0.0175 | 3 | 18 | 2 | 4.5 | 4.7 | 2 | 15.14 | 10.76 | 2 | 0.71 | 0.98 | 8.57 | 8.39 | 2 |
| Ash/Acorn/Birch | Branch | 13D | 13C | 5 | 0.005 | 4 | 21 | 2 | 4.4 | 4.2 | 2 | 12.21 | 12.14 | 2 | 0.99 | 1.01 | 5.08 | 5.13 | 2 |
| Ash/Acorn/Birch | Branch | 13C | 13B | 8 | 0.008 | 4 | 21 | 2 | 4.2 | 5.0 | 2 | 15.45 | 15.31 | 2 | 0.99 | 1.01 | 6.42 | 6.50 | 2 |
| Ash/Acorn/Birch | Branch | 13B | 13A | 10 | 0.01 | 5 | 24 | 2 | 4.8 | 4.8 | 2 | 24.65 | 18.20 | 2 | 0.74 | 0.99 | 7.85 | 7.76 | 2 |
| Ash/Acorn/Birch | Branch | 13A | 13 | 7 | 0.007 | 5 | 24 | 2 | 4.8 | 7.5 | 2 | 20.63 | 20.48 | 2 | 0.99 | 1.01 | 6.57 | 6.64 | 2 |
| East Birch | Branch | 13I | 13H | | | | | | | | | | | | | | | | |
| East Birch | Branch | 13H | 13 | 4 | 0.004 | 4 | 21 | 2 | 4.0 | 4.1 | 2 | 10.92 | 9.29 | 2 | 0.85 | 1.02 | 4.54 | 4.62 | 2 |
| W. Cedar | Branch | 14D | 14C | | | | | | | | | | | | | | | | |
| W. Cedar | Branch | 14C | 14B | 6 | 0.006 | 3 | 18 | 2 | 4.0 | 4.3 | 2 | 8.87 | 8.26 | 2 | 0.93 | 1.03 | 5.02 | 5.15 | 2 |
| W. Cedar | Branch | 14B | 14A | 17 | 0.02 | 3 | 18 | 2 | 4.3 | 4.6 | 2 | 16.19 | 12.15 | 2 | 0.75 | 0.99 | 9.16 | 9.11 | 2 |
| W. Cedar | Branch | 14A | 14 | 7 | 0.007 | 4 | 21 | 2 | 4.3 | 5.2 | 2 | 14.45 | 14.26 | 2 | 0.99 | 1.01 | 6.01 | 6.09 | 2 |
| E. Cedar | Branch | 14E | 14F | | | | | | | | | | | | | | | | |
| E. Cedar | Branch | 14F | 14 | 7 | 0.007 | 3 | 18 | 2 | 4.0 | 4.2 | 2 | 9.58 | 6.17 | 2 | 0.64 | 0.95 | 5.42 | 5.17 | 2 |
| Aspen | Branch | 15B | 15A | | | | | | | | | | | | | | | | |
| Aspen | Branch | 15A | 15 | 9 | 0.009 | 3 | 18 | 2 | 4.0 | 4.1 | 2 | 10.86 | 7.42 | 2 | 0.68 | 0.97 | 6.15 | 5.96 | 2 |
| W. Ashmont | Branch | 16C | 16B | | | | | | | | | | | | | | | | |
| W. Ashmont | Branch | 16B | 16A | 11 | 0.011 | 3 | 18 | 2 | 4.0 | 4.3 | 2 | 12.01 | 11.89 | 2 | 0.99 | 1.01 | 6.79 | 6.88 | 2 |
| W. Ashmont | Branch | 16A | 16 | 9 | 0.009 | 4 | 21 | 2 | 4.1 | 5.3 | 2 | 16.38 | 16.01 | 2 | 0.98 | 1.02 | 6.81 | 6.94 | 2 |
| E. Ashmont | Branch | 16E | 16D | | | | | | | | | | | | | | | | |
| E. Ashmont | Branch | 16D | 16 | 16 | 0.0175 | 3 | 18 | 2 | 4.0 | 4.0 | 2 | 15.14 | 9.56 | 2 | 0.63 | 0.95 | 8.57 | 8.15 | 2 |
| Highland | Branch | 17B | 17A | | | | | | | | | | | | | | | | |
| Highland | Branch | 17A | 17 | 20 | 0.0401 | 7 | 30 | 2 | 4.0 | 4.02 | 2 | 89.52 | 9.87 | 2 | 0.11 | 0.54 | 18.24 | 9.93 | 2 |
| Maple/Redwood | Trunk | 6 | 7 | | | | | | | | | | | | | | | | |
| Alpine | Trunk | 7 | 8 | 14 | 0.014 | 5 | 24 | 2 | 4.0 | 7.0 | 2 | 29.17 | 22.19 | 2 | 0.76 | 1.00 | 9.29 | 9.25 | 2 |
| Oak | Trunk | 8 | 9 | 13 | 0.013 | 8 | 36 | 2 | 6.0 | 5.5 | 2 | 82.88 | 35.74 | 2 | 0.43 | 0.84 | 11.73 | 9.91 | 2 |
| Walnut | Trunk | 9 | 10 | 10 | 0.01 | 8 | 36 | 2 | 5.5 | 6.7 | 2 | 72.69 | 42.99 | 2 | 0.59 | 0.93 | 10.28 | 9.60 | 2 |
| Forest | Trunk | 10 | 11 | 8 | 0.008 | 8 | 36 | 2 | 6.7 | 9.2 | 2 | 65.02 | 63.40 | 2 | 0.98 | 1.02 | 9.20 | 9.38 | 2 |
| Elm | Trunk | 11 | 12 | 6 | 0.006 | 9 | 42 | 2 | 8.7 | 11.0 | 2 | 84.93 | 77.59 | 2 | 0.91 | 1.03 | 8.83 | 9.05 | 2 |
| Forest | Trunk | 12 | 13 | 5 | 0.005 | 10 | 48 | 2 | 10.5 | 11.3 | 2 | 110.70 | 102.79 | 2 | 0.93 | 1.03 | 8.81 | 9.03 | 2 |
| Birch | Trunk | 13 | 14 | 5 | 0.005 | 11 | 60 | 2 | 10.3 | 11.0 | 2 | 200.71 | 131.39 | 2 | 0.65 | 0.96 | 10.22 | 9.79 | 2 |
| Cedar | Trunk | 14 | 15 | 4 | 0.004 | 11 | 60 | 2 | 11.0 | 12.7 | 2 | 179.52 | 144.73 | 2 | 0.81 | 1.01 | 9.14 | 9.22 | 2 |
| Aspen | Trunk | 15 | 16 | 4 | 0.004 | 11 | 60 | 2 | 12.7 | 11.6 | 2 | 179.52 | 149.02 | 2 | 0.83 | 1.01 | 9.14 | 9.27 | 2 |
| Ashmont | Trunk | 16 | 17 | 4 | 0.004 | 11 | 60 | 2 | 11.6 | 8.5 | 2 | 179.52 | 168.06 | 2 | 0.93 | 1.03 | 9.14 | 9.38 | 2 |
| Highland | Trunk | 17 | 18 | 4 | 0.004 | 11 | 60 | 2 | 8.5 | 5.2 | 2 | 179.52 | 171.06 | 2 | 0.95 | 1.02 | 9.14 | 9.38 | 2 |

### *5.1.2 Sizing the sewer pipes and their slopes*

The calculations for selecting a feasible solution to the storm drainage design are shown in Table 5-7. Using this template, the engineer selects from among 20 available sewer sizes and 20 assumed slopes. It is convenient to number these options 1–20 and then use a lookup table to input the associated pipe diameters and slopes. The design requirements for this sewer network are as follow:

1. The minimum depth of cover is 4 ft.
2. Stormwater can flow in the street for the first section only.
3. The flow capacity of the pipe must exceed the estimated peak flow.
4. No downstream pipe can be smaller in diameter than its upstream pipe.
5. Where multiple pipes enter a single manhole, the depth of the manhole is the maximum required depth.
6. The minimum velocity of flow in the sewer under design conditions is 3.0 ft/s. The model computes the velocity for full or partially full pipes as appropriate.

Using a trial and error procedure, the pipe diameters and slopes are varied until all of the above conditions are satisfied. This spreadsheet template is an advanced way to do storm sewer design. In a typical design, only a few scenarios are evaluated before settling on a final design. The feasible solution shown in Table 5-7 is based on several trials that included evaluation of the system cost. Thus, diameters and slopes were varied in order to reduce the total cost. The basic tradeoff in conventional storm sewer design is that a larger pipe can be laid at a flatter slope. Thus, added pipe costs are offset by reduced excavation costs.

Column 8 of Table 5-7 is the design diameter in inches, which is restricted to a given set of diameters within a lookup table. Column 6 is the slope of the pipe, which is also restricted to a group of slopes from a lookup table. Column 10 is the computed upstream crown elevation. Column 11 is the computation of the downstream crown elevation. Each of the calculations within each link (row) is matched to subsequent downstream elevations, and a check is made for the minimum cover constraint in column 11. Column 18 is the computation of the full flow within the pipe, and column 19 is the computation of the pipe flowing under the design conditions. The choice of pipe diameter is restricted such that the capacity of a pipe is not exceeded. Next the ratios of $Q/Q_f$ are calculated in column 16, which then leads to the $v/v_f$ in column 17 using the ratios for a partially full pipe. The velocity of the pipe flowing full is calculated by dividing the full flow rate in column 12 by the cross sectional area of the pipe(function of the pipe diameter) and is listed in column 17. Column 18 is velocity of the partially full pipe, calculated from the ratio in column 16. Details of the pipe hydraulics are described in Miles and Heaney (1988).

Table 5-8. Sewer Network Design Cost

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Street | Type | Nodes From | Nodes To | Length (ft) | Ground Elev. Upper (ft) | Ground Elev. Lower (ft) | Soil | Pipe Diameter (in) | Pipe Slope | Side Slope Horz./Vert. | Upper Invert Elev. (ft) | Lower Invert Elev. (ft) | Pipe Cost ($) | Avg. Depth (ft) | Avg. Width (ft) | Total Volume (yd³) | Excavation Cost ($/yd³) | Excavation Cost Total ($) | Bedding Cost ($) | Manhole Depth (ft) | Manhole Cost ($) | Total Cost ($) |
| Maple/Redwood | Branch | 1 | 2 | 279 | 207.0 | 206.7 | Silt | | | | | | | | | | | | | | | |
| Maple/Redwood | Branch | 2 | 3 | 299 | 206.7 | 206.7 | Silt | 18 | 0.004 | 1.50 | 201.19 | 200.00 | 5,673 | 6.10 | 10.65 | 718 | 6.72 | 4,821 | 3,099 | 5.5 | 2,360 | 15,953 |
| Maple/Redwood | Branch | 3 | 4 | 272 | 206.7 | 207.3 | Silt | 21 | 0.003 | 1.50 | 200.00 | 199.18 | 6,263 | 7.43 | 12.02 | 901 | 6.72 | 6,052 | 3,805 | 6.69 | 2,834 | 18,754 |
| Maple/Redwood | Branch | 4 | 5 | 148 | 207.3 | 207.3 | Silt | 21 | 0.004 | 1.50 | 199.18 | 198.59 | 3,396 | 8.46 | 33.65 | 1557 | 6.72 | 10,461 | 1,954 | 8.17 | 3,411 | 19,221 |
| Maple/Redwood | Branch | 5 | 6 | 325 | 207.3 | 207.3 | Silt | 24 | 0.003 | 1.50 | 198.59 | 197.61 | 8,964 | 9.25 | 14.91 | 1658 | 6.72 | 11,138 | 4,753 | 8.76 | 3,640 | 28,494 |
| Alpine | Branch | 7B | 7A | 367 | 207.0 | 206.0 | Silt | | | 1.50 | | | | | | | 6.72 | | | | | |
| Alpine | Branch | 7A | 7 | 367 | 206.0 | 206.0 | Silt | 21 | 0.004 | 1.50 | 200.28 | 198.81 | 8,451 | 6.48 | 10.80 | 936 | 6.72 | 6,286 | 4,864 | 5.75 | 2,459 | 22,061 |
| Oak | Branch | 8D | 8C | 328 | 208.3 | 208.0 | Silt | | | 1.50 | | | | | | | 6.72 | | | | | |
| Oak | Branch | 8C | 8B | 328 | 208.0 | 204.1 | Silt | 21 | 0.013 | 1.50 | 202.25 | 197.99 | 7,544 | 5.91 | 9.75 | 700 | 6.72 | 4,703 | 4,342 | 5.75 | 2,459 | 19,049 |
| Oak | Branch | 8B | 8A | 328 | 204.1 | 203.7 | Silt | 21 | 0.005 | 1.50 | 197.99 | 196.35 | 7,544 | 6.73 | 10.97 | 898 | 6.72 | 6,030 | 4,342 | 6.08 | 2,589 | 20,506 |
| Oak | Branch | 8A | 8 | 328 | 203.7 | 203.4 | Silt | 24 | 0.005 | 1.50 | 196.35 | 194.71 | 9,053 | 8.04 | 13.07 | 1277 | 6.72 | 8,579 | 4,800 | 7.39 | 3,107 | 25,538 |
| Walnut | Branch | 9B | 9A | 394 | 207.0 | 204.1 | Silt | | | 1.50 | | | | | | | 6.72 | | | | | |
| Walnut | Branch | 9A | 9 | 394 | 204.1 | 202.4 | Silt | 21 | 0.005 | 1.50 | 198.32 | 196.35 | 9,062 | 5.91 | 9.75 | 841 | 6.72 | 5,652 | 5,216 | 5.75 | 2,459 | 22,389 |
| W. Forest | Branch | 10E | 10D | 394 | 210.0 | 207.3 | Silt | | | 1.50 | | | | | | | 6.72 | | | | | |
| W. Forest | Branch | 10D | 10C | 344 | 207.3 | 206.0 | Silt | 21 | 0.005 | 1.50 | 201.60 | 199.87 | 7,923 | 5.96 | 9.81 | 745 | 6.72 | 5,006 | 4,560 | 5.75 | 2,459 | 19,949 |
| W. Forest | Branch | 10C | 10B | 328 | 206.0 | 204.1 | Silt | 21 | 0.006 | 1.50 | 199.87 | 197.91 | 7,546 | 6.16 | 10.12 | 757 | 6.72 | 5,086 | 4,343 | 6.16 | 2,622 | 19,598 |
| W. Forest | Branch | 10B | 10A | 328 | 204.1 | 203.4 | Silt | 24 | 0.005 | 1.50 | 197.91 | 196.27 | 9,055 | 6.65 | 10.98 | 887 | 6.72 | 5,961 | 4,801 | 6.16 | 2,622 | 22,440 |
| W. Forest | Branch | 10A | 10 | 246 | 203.4 | 201.4 | Silt | 24 | 0.005 | 1.50 | 196.27 | 195.03 | 6,791 | 6.78 | 11.16 | 689 | 6.72 | 4,630 | 3,601 | 7.14 | 3,011 | 18,033 |
| E. Forest | Branch | 12B | 12A | 328 | 208.3 | 206.7 | Silt | | | 1.50 | | | | | | | 6.72 | | | | | |
| E. Forest | Branch | 12A | 12 | 328 | 206.7 | 203.7 | Silt | 18 | 0.01 | 1.50 | 201.19 | 197.91 | 6,232 | 5.66 | 9.25 | 636 | 6.72 | 4,273 | 3,405 | 5.50 | 2,360 | 16,269 |
| Sycamore/Elm | Branch | 11G | 11F | 328 | 215.9 | 212.3 | Clay | | | 1.00 | | | | | | | 7.09 | | | | | |
| Sycamore/Elm | Branch | 11F | 11E | 279 | 212.3 | 210.0 | Clay | 18 | 0.01 | 1.00 | 206.77 | 203.98 | 5,298 | 5.75 | 6.50 | 386 | 7.09 | 2,732 | 2,269 | 5.50 | 2,360 | 12,860 |
| Sycamore/Elm | Branch | 11E | 11D | 262 | 210.0 | 209.6 | Clay | 21 | 0.005 | 1.00 | 203.98 | 202.67 | 6,037 | 6.48 | 7.36 | 464 | 7.09 | 3,287 | 2,778 | 5.99 | 2,556 | 14,658 |
| Sycamore/Elm | Branch | 11D | 11C | 82 | 209.6 | 208.7 | Clay | 24 | 0.003 | 1.00 | 202.67 | 202.42 | 2,264 | 6.61 | 7.61 | 153 | 7.09 | 1,082 | 952 | 6.98 | 2,945 | 7,243 |
| Sycamore/Elm | Branch | 11C | 11B | 328 | 208.7 | 204.1 | Clay | 24 | 0.014 | 1.00 | 202.42 | 197.83 | 9,055 | 6.24 | 7.24 | 549 | 7.09 | 3,888 | 3,809 | 6.24 | 2,653 | 19,406 |
| Sycamore/Elm | Branch | 11B | 11A | 328 | 204.1 | 202.8 | Silt | 24 | 0.005 | 1.50 | 197.83 | 196.19 | 9,055 | 6.40 | 10.60 | 825 | 6.72 | 5,541 | 4,801 | 6.24 | 2,653 | 22,051 |
| Sycamore/Elm | Branch | 11A | 11 | 295 | 202.8 | 202.1 | Silt | 27 | 0.003 | 1.50 | 196.19 | 195.30 | 9,714 | 6.66 | 11.15 | 814 | 6.72 | 5,471 | 4,321 | 6.57 | 2,783 | 22,289 |
| Ash/Acorn/Birch | Branch | 13G | 13F | 328 | 229.0 | 221.8 | Clay | | | 1.00 | | | | | | | 7.09 | | | | | |
| Ash/Acorn/Birch | Branch | 13F | 13E | 328 | 221.8 | 216.5 | Clay | 18 | 0.0175 | 1.00 | 216.28 | 210.54 | 6,234 | 5.75 | 6.50 | 454 | 7.09 | 3,214 | 2,870 | 5.50 | 2,360 | 14,477 |
| Ash/Acorn/Birch | Branch | 13E | 13D | 328 | 216.5 | 211.0 | Clay | 18 | 0.0175 | 1.00 | 210.54 | 204.80 | 6,234 | 6.07 | 6.82 | 504 | 7.09 | 3,570 | 2,870 | 5.99 | 2,556 | 15,029 |
| Ash/Acorn/Birch | Branch | 13D | 13C | 82 | 211.0 | 210.3 | Clay | 21 | 0.005 | 1.00 | 204.80 | 204.39 | 1,886 | 6.03 | 6.91 | 127 | 7.09 | 897 | 868 | 6.16 | 2,621 | 6,273 |
| Ash/Acorn/Birch | Branch | 13C | 13B | 394 | 210.3 | 208.0 | Clay | 21 | 0.008 | 1.00 | 204.39 | 201.24 | 9,055 | 6.34 | 7.21 | 666 | 7.09 | 4,722 | 4,167 | 5.91 | 2,523 | 20,468 |
| Ash/Acorn/Birch | Branch | 13B | 13A | 394 | 208.0 | 204.1 | Silt | 24 | 0.01 | 1.50 | 201.24 | 197.30 | 10,866 | 6.76 | 11.14 | 1099 | 6.72 | 7,383 | 5,761 | 6.76 | 2,861 | 26,871 |
| Ash/Acorn/Birch | Branch | 13A | 13 | 394 | 204.1 | 204.1 | Silt | 24 | 0.007 | 1.50 | 197.30 | 194.55 | 10,866 | 8.14 | 13.21 | 1568 | 6.72 | 10,535 | 5,761 | 6.76 | 2,861 | 30,023 |
| East Birch | Branch | 13I | 13H | 262 | 206.7 | 205.7 | Silt | | | 1.50 | | | | | | | 6.72 | | | | | |
| East Birch | Branch | 13H | 13 | 262 | 205.7 | 204.7 | Silt | 21 | 0.004 | 1.50 | 199.96 | 198.91 | 6,026 | 5.76 | 9.56 | 536 | 6.72 | 3,599 | 3,468 | 5.75 | 2,459 | 15,552 |
| W. Cedar | Branch | 14D | 14C | 262 | 212.9 | 210.6 | Clay | | | 1.00 | | | | | | | 7.09 | | | | | |
| W. Cedar | Branch | 14C | 14B | 262 | 210.6 | 209.3 | Clay | 18 | 0.006 | 1.00 | 205.13 | 203.55 | 4,987 | 5.63 | 6.38 | 349 | 7.09 | 2,476 | 2,136 | 5.50 | 2,360 | 11,958 |
| W. Cedar | Branch | 14B | 14A | 262 | 209.3 | 204.4 | Clay | 18 | 0.02 | 1.00 | 203.55 | 198.30 | 4,987 | 5.93 | 6.68 | 385 | 7.09 | 2,726 | 2,136 | 5.76 | 2,464 | 12,313 |
| W. Cedar | Branch | 14A | 14 | 262 | 204.4 | 203.4 | Clay | 21 | 0.007 | 1.00 | 198.30 | 196.47 | 6,037 | 6.52 | 7.39 | 468 | 7.09 | 3,319 | 2,778 | 6.09 | 2,595 | 14,729 |
| E. Cedar | Branch | 14E | 14F | 262 | 208.3 | 205.1 | Clay | | | 1.00 | | | | | | | 7.09 | | | | | |
| E. Cedar | Branch | 14F | 14 | 262 | 205.1 | 203.4 | Clay | 18 | 0.007 | 1.00 | 199.55 | 197.71 | 4,987 | 5.60 | 6.35 | 345 | 7.09 | 2,449 | 2,136 | 5.50 | 2,360 | 11,931 |
| Aspen | Branch | 15B | 15A | 328 | 207.3 | 206.4 | Clay | | | 1.00 | | | | | | | 7.09 | | | | | |
| Aspen | Branch | 15A | 15 | 262 | 206.4 | 204.1 | Clay | 18 | 0.009 | 1.00 | 200.86 | 198.50 | 4,978 | 5.53 | 6.28 | 337 | 7.09 | 2,389 | 2,132 | 5.50 | 2,360 | 11,858 |
| W. Ashmont | Branch | 16C | 16B | 328 | 213.3 | 206.7 | Rock | | | 0.00 | | | | | | | 86.29 | | | | | |
| W. Ashmont | Branch | 16B | 16A | 328 | 206.7 | 203.4 | Rock | 18 | 0.011 | 0.00 | 201.19 | 197.58 | 6,232 | 5.66 | 0.75 | 52 | 86.29 | 4,452 | 1,189 | 5.50 | 2,360 | 14,233 |
| W. Ashmont | Branch | 16A | 16 | 246 | 203.4 | 202.4 | Rock | 21 | 0.009 | 0.00 | 197.58 | 195.37 | 5,659 | 6.44 | 0.88 | 51 | 86.29 | 4,433 | 1,302 | 5.83 | 2,490 | 13,885 |
| E. Ashmont | Branch | 16E | 16D | 262 | 210.0 | 206.7 | Rock | | | 0.00 | | | | | | | 86.29 | | | | | |
| E. Ashmont | Branch | 16D | 16 | 246 | 206.7 | 202.4 | Rock | 18 | 0.0175 | 0.00 | 201.19 | 196.88 | 4,675 | 5.52 | 0.75 | 38 | 86.29 | 3,256 | 892 | 5.50 | 2,360 | 11,182 |
| Highland | Branch | 17B | 17A | 262 | 211.3 | 208.3 | Rock | | | 0.00 | | | | | | | 86.29 | | | | | |
| Highland | Branch | 17A | 17 | 246 | 208.3 | 198.5 | Rock | 30 | 0.0401 | 0.00 | 201.83 | 191.97 | 13,727 | 6.51 | 1.25 | 74 | 86.29 | 6,398 | 1,339 | 6.50 | 2,757 | 24,221 |
| Maple/Redwood | Trunk | 6 | 7 | | | | Silt | | | | | | | | | | | | | | | |
| Alpine | Trunk | 7 | 8 | 400 | 206.0 | 203.4 | Silt | 24 | 0.014 | 1.50 | 200.03 | 194.43 | 11,047 | 7.49 | 12.23 | 1358 | 6.72 | 9,125 | 5,857 | | | 26,029 |
| Oak | Trunk | 8 | 9 | 36 | 203.4 | 202.4 | Silt | 36 | 0.013 | 1.50 | 194.43 | 193.96 | 2,685 | 8.72 | 14.58 | 170 | 6.72 | 1,142 | 528 | | | 4,355 |
| Walnut | Trunk | 9 | 10 | 220 | 202.4 | 201.4 | Silt | 36 | 0.01 | 1.50 | 193.96 | 191.76 | 16,354 | 9.07 | 15.11 | 1116 | 6.72 | 7,494 | 3,217 | | | 27,065 |
| Forest | Trunk | 10 | 11 | 230 | 201.4 | 202.1 | Silt | 36 | 0.008 | 1.50 | 191.76 | 189.93 | 17,086 | 10.92 | 17.89 | 1662 | 6.72 | 11,165 | 3,361 | | | 31,612 |
| Elm | Trunk | 11 | 12 | 112 | 202.1 | 203.7 | Clay | 42 | 0.006 | 1.00 | 189.93 | 189.26 | 9,526 | 13.33 | 15.08 | 830 | 7.09 | 5,882 | 1,295 | | | 16,704 |
| Forest | Trunk | 12 | 13 | 95 | 203.7 | 204.1 | Clay | 48 | 0.005 | 1.00 | 189.26 | 188.78 | 9,733 | 14.88 | 16.88 | 885 | 7.09 | 6,275 | 1,105 | | | 17,113 |
| Birch | Trunk | 13 | 14 | 282 | 204.1 | 203.4 | Clay | 60 | 0.005 | 1.00 | 188.78 | 187.37 | 41,391 | 15.66 | 18.16 | 2973 | 7.09 | 21,066 | 3,276 | | | 65,734 |
| Cedar | Trunk | 14 | 15 | 246 | 203.4 | 204.1 | Clay | 60 | 0.004 | 1.00 | 187.37 | 186.39 | 36,097 | 16.86 | 19.36 | 2974 | 7.09 | 21,081 | 2,857 | | | 60,035 |
| Aspen | Trunk | 15 | 16 | 144 | 204.1 | 202.4 | Clay | 60 | 0.004 | 1.00 | 186.39 | 185.81 | 21,177 | 17.15 | 19.65 | 1801 | 7.09 | 12,767 | 1,676 | | | 35,620 |
| Ashmont | Trunk | 16 | 17 | 203 | 202.4 | 198.5 | Rock | 60 | 0.004 | 0.00 | 185.81 | 185.00 | 29,840 | 15.06 | 2.50 | 284 | 86.29 | 24,466 | 1,107 | | | 55,414 |
| Highland | Trunk | 17 | 18 | 164.04 | 198.5 | 194.6 | Rock | 60 | 0.004 | 0.00 | 185.00 | 184.34 | 24,085 | 11.85 | 2.50 | 180 | 86.29 | 15,534 | 893 | | | 40,492 |

5.1.3 Sewer system cost evaluation

Finally, Table 5-8 does the cost estimation for the entire system. Column 10 is the pipe slope from Table 5-7. Based upon the soil type of column 8, and a lookup table, a side slope ratio of horizontal to vertical is chosen in column 11. Column 12 is the upstream invert elevation, computed by multiplying the slope of column 10 by the pipe length of column 5 and subtracting this from column 13. Column 13 is the downstream invert elevation, computed by using the pipe diameter, the previous link invert elevation, and the slope from column 10.

The ground elevations, soil types, cost of the pipes and manholes, and excavation costs are calculated for a mix of selected pipe diameter and slope scenarios. Pipe costs are estimated using lookup table values in Tables 5.9 or 5.10 for CMP or RCP pipe, respectively. These costs are computed in column 14 of Table 5-8.

**Table 5-9. Lookup Table for Corrugated Metal Pipe (Adapted from RS Means, 1996a)**

| Diameter | CMP Pipe Cost (1/99 $/ft) |
|---|---|
| 8 | 9.40 |
| 10 | 11.80 |
| 12 | 14.40 |
| 15 | 18.40 |
| 18 | 20.90 |
| 24 | 30.10 |
| 30 | 37.20 |
| 36 | 54.80 |
| 48 | 81.60 |
| 60 | 118.20 |
| 72 | 179.50 |

Excavation costs depend on the volume of excavation and the unit excavation costs. The lookup table values for these costs are listed in Table 5-11. The volume of excavation is calculated as follows:

$$V = \frac{LWH}{27} \tag{5-7}$$

Where

$V$ = excavation volume, $yd^3$

$L$ = distance between manholes, ft

$W$ = the average of the trench top and bottom widths (bottom is $D$+1.5), ft

$H$ = average excavation depth, ft

**Table 5-10. Lookup table for reinforced concrete pipe (Adapted from RS Means, 1996a).**

| Diameter (in.) | RCP Pipe Cost (1/99 $/ft) |
|---|---|
| 12 | 15.70 |
| 15 | 16.60 |
| 18 | 19.00 |
| 21 | 23.00 |
| 24 | 27.60 |
| 27 | 32.90 |
| 30 | 55.80 |
| 36 | 74.40 |
| 42 | 85.40 |
| 48 | 102.30 |
| 60 | 146.70 |
| 72 | 192.60 |
| 84 | 288.90 |
| 96 | 355.60 |

The average depth of the excavation is computed in column 15 of Table 5-8. The average width of the excavation is calculated as an average of the top and bottom widths, and is listed in column 16 of Table 5-8. The total volume is computed using equation 5.8 and results listed in column 17.

Excavation costs, $C_{ex}$, are calculated as:

$$C_{ex} = c_{ex} V \tag{5-8}$$

The unit excavation cost, $c_{ex}$, is a function of the soil type, which were explained in Table 3-2, and are listed again in Table 5-9. These costs are computed in column 18 and 19 of Table 5-8.

**Table 5-11. Excavation Costs (Adapted from RS Means, 1996a)**

| Soil Type | Horizontal | Vertical | Excavation Cost (1/99 $/yr$^3$) |
|---|---|---|---|
| Clay | 1 | 1 | 7.09 |
| Rock | 0 | 1 | 86.29 |
| Sand | 2 | 1 | 6.12 |
| Silt | 1.5 | 1 | 6.72 |

Bedding costs are evaluated based upon a two variable lookup function that uses side slope and diameter to determine costs. The lookup values are presented in Table 5-12, and the results are presented in column 20 of Table 5-8.

Manhole costs are estimated using the following equation:

$$C_{mh} = 482H^{0.9317} \qquad (5\text{-}9)$$

Where

$C_m$ = cost of manhole, 1/99 \$

$H$ = height of manhole, ft
(maximum difference between the ground elevation and the invert elevations of sewers entering the manhole)

These costs are computed in column 22 of Table 5-8.

## 5.2 Scenario Analysis

The results shown in Tables 5-1, 5-7, and 5-8 reflect the costs for sets of such assumed input conditions as topography, land use, design storm, performance criteria, and pipe cost. The power of the spreadsheet is its ability to enable what-if design analysis. By systematically changing one or more of the input variables the impact of these variables on the total cost is more easily assessed. The classic approach is to change and assess one variable at a time. However, sensitivity analysis may be performed for a finite number of scenarios wherein many, if not all, of the input assumptions are allowed to vary, and to find the cost for each scenario. The potential number of scenarios for this problem is huge. For this initial effort, only a very small number of scenarios were selected, in order to show the impact of various scenarios on the total cost. An important caveat in this sensitivity analysis is that the base solution's effectiveness is unknown. Thus, the sensitivity analysis is done for a solution of unknown quality. This limitation can be removed in future work by using intelligent search techniques to find very good, if not optimal, solutions for each scenario. The following sub-sections describe a limited number of input variables that can be assessed to test the sensitivity of the final cost to various assumptions.

Table 5-12. Bedding Costs (Adapted form RS Means, 1996a)

| Horizontal | Vertical | H/V | Diameter (in.) | Trench width (ft) | Cost (1/99 $/ft) |
|---|---|---|---|---|---|
| 0 | 1 | 0 | 6 | 1 | 0.92 |
| 0 | 1 | 0 | 8 | 2 | 2.00 |
| 0 | 1 | 0 | 10 | 2 | 2.07 |
| 0 | 1 | 0 | 12 | 2 | 2.12 |
| 0 | 1 | 0 | 14 | 3 | 3.47 |
| 0 | 1 | 0 | 15 | 3 | 3.51 |
| 0 | 1 | 0 | 16 | 3 | 3.57 |
| 0 | 1 | 0 | 18 | 3 | 3.62 |
| 0 | 1 | 0 | 20 | 4 | 5.25 |
| 0 | 1 | 0 | 21 | 4 | 5.29 |
| 0 | 1 | 0 | 24 | 4 | 5.44 |
| 0 | 1 | 0 | 30 | 4 | 5.55 |
| 0 | 1 | 0 | 32 | 6 | 9.72 |
| 0 | 1 | 0 | 36 | 6 | 9.98 |
| 0 | 1 | 0 | 48 | 7 | 13.01 |
| 0 | 1 | 0 | 60 | 8 | 16.23 |
| 0 | 1 | 0 | 72 | 10 | 23.39 |
| 0 | 1 | 0 | 84 | 12 | 31.80 |
| 0.5 | 1 | 0.5 | 6 | 1 | 1.90 |
| 0.5 | 1 | 0.5 | 8 | 2 | 3.16 |
| 0.5 | 1 | 0.5 | 10 | 2 | 3.43 |
| 0.5 | 1 | 0.5 | 12 | 2 | 3.67 |
| 0.5 | 1 | 0.5 | 14 | 3 | 5.25 |
| 0.5 | 1 | 0.5 | 15 | 3 | 5.39 |
| 0.5 | 1 | 0.5 | 16 | 3 | 5.55 |
| 0.5 | 1 | 0.5 | 18 | 3 | 5.88 |
| 0.5 | 1 | 0.5 | 20 | 4 | 7.77 |
| 0.5 | 1 | 0.5 | 21 | 4 | 7.95 |
| 0.5 | 1 | 0.5 | 24 | 4 | 8.52 |
| 0.5 | 1 | 0.5 | 30 | 4 | 9.56 |
| 0.5 | 1 | 0.5 | 32 | 6 | 14.06 |
| 0.5 | 1 | 0.5 | 36 | 6 | 15.08 |
| 0.5 | 1 | 0.5 | 48 | 7 | 20.58 |
| 0.5 | 1 | 0.5 | 60 | 8 | 26.81 |
| 0.5 | 1 | 0.5 | 72 | 10 | 37.47 |
| 0.5 | 1 | 0.5 | 84 | 12 | 49.71 |
| 1 | 1 | 1 | 6 | 1 | 2.90 |
| 1 | 1 | 1 | 8 | 2 | 4.36 |
| 1 | 1 | 1 | 10 | 2 | 4.77 |
| 1 | 1 | 1 | 12 | 2 | 5.25 |
| 1 | 1 | 1 | 14 | 3 | 7.06 |
| 1 | 1 | 1 | 15 | 3 | 7.30 |
| 1 | 1 | 1 | 16 | 3 | 7.56 |
| 1 | 1 | 1 | 18 | 3 | 8.14 |
| 1 | 1 | 1 | 20 | 4 | 10.28 |
| 1 | 1 | 1 | 21 | 4 | 10.59 |
| 1 | 1 | 1 | 24 | 4 | 11.61 |
| 1 | 1 | 1 | 30 | 4 | 13.50 |
| 1 | 1 | 1 | 32 | 6 | 18.46 |
| 1 | 1 | 1 | 36 | 6 | 20.17 |
| 1 | 1 | 1 | 48 | 7 | 28.17 |
| 1 | 1 | 1 | 60 | 8 | 37.40 |
| 1 | 1 | 1 | 72 | 10 | 51.76 |
| 1 | 1 | 1 | 84 | 12 | 67.70 |
| 1.5 | 1 | 1.5 | 6 | 1 | 3.91 |
| 1.5 | 1 | 1.5 | 8 | 2 | 5.69 |
| 1.5 | 1 | 1.5 | 10 | 2 | 6.15 |
| 1.5 | 1 | 1.5 | 12 | 2 | 6.81 |

| Horizontal | Vertical | H/V | Diameter (in.) | Trench width (ft) | Cost (1/99 $/ft) |
|---|---|---|---|---|---|
| 1.5 | 1 | 1.5 | 14 | 3 | 8.83 |
| 1.5 | 1 | 1.5 | 15 | 3 | 9.18 |
| 1.5 | 1 | 1.5 | 16 | 3 | 9.56 |
| 1.5 | 1 | 1.5 | 18 | 3 | 10.38 |
| 1.5 | 1 | 1.5 | 20 | 4 | 12.80 |
| 1.5 | 1 | 1.5 | 21 | 4 | 13.24 |
| 1.5 | 1 | 1.5 | 24 | 4 | 14.63 |
| 1.5 | 1 | 1.5 | 30 | 4 | 17.64 |
| 1.5 | 1 | 1.5 | 32 | 6 | 22.77 |
| 1.5 | 1 | 1.5 | 36 | 6 | 25.23 |
| 1.5 | 1 | 1.5 | 48 | 7 | 35.76 |
| 1.5 | 1 | 1.5 | 60 | 8 | 48.21 |
| 1.5 | 1 | 1.5 | 72 | 10 | 65.65 |
| 1.5 | 1 | 1.5 | 84 | 12 | 86.16 |
| 2 | 1 | 2 | 6 | 1 | 5.01 |
| 2 | 1 | 2 | 8 | 2 | 6.73 |
| 2 | 1 | 2 | 10 | 2 | 7.49 |
| 2 | 1 | 2 | 12 | 2 | 8.37 |
| 2 | 1 | 2 | 14 | 3 | 10.59 |
| 2 | 1 | 2 | 15 | 3 | 11.04 |
| 2 | 1 | 2 | 16 | 3 | 11.54 |
| 2 | 1 | 2 | 18 | 3 | 12.66 |
| 2 | 1 | 2 | 20 | 4 | 15.32 |
| 2 | 1 | 2 | 21 | 4 | 15.89 |
| 2 | 1 | 2 | 24 | 4 | 17.71 |
| 2 | 1 | 2 | 31 | 4 | 21.61 |
| 2 | 1 | 2 | 32 | 6 | 27.15 |
| 2 | 1 | 2 | 36 | 6 | 30.22 |
| 2 | 1 | 2 | 48 | 7 | 43.22 |
| 2 | 1 | 2 | 60 | 8 | 58.67 |
| 2 | 1 | 2 | 72 | 10 | 79.32 |
| 2 | 1 | 2 | 84 | 12 | 103.94 |
| | | | | | |

### *5.2.1 Management of the demand for imperviousness*

Imperviousness can be reduced by designing narrower streets and driveways, reducing parking requirements, etc. Two cases are:

| Case | Imperviousness |
|---|---|
| 1 | Present values |
| 2 | 0.7 * Present values |

### *5.2.2 Management of land use*

The assumed land use for this example is representative of a typical mix of residential, commercial, and public land use. Two other scenarios are all low density and all high density. Thus, the three land use scenarios are:

| Case | Land Use |
|---|---|
| 1 | Mixed |
| 2 | All residential at 2 dwelling units/acre-commercial and school are the same. |
| 3 | All residential at 10 dwelling units/acre-commercial and school are the same. |

*5.2.3 Effect of recurrence interval*

The selected design storm recurrence intervals are assumed to range from 2 to 100 yr. A 2 yr level represents a minimum level of service, whereas a 100 yr level would represent an upper limit on drainage systems. Three cases can be considered:

| Case | Recurrence Interval (yrs) |
|---|---|
| 1 | 2 |
| 2 | 5 |
| 3 | 100 |

*5.2.4 Effect of climate*

The sophistication of the drainage system is expected to vary widely from the wetter areas of the country with high intensity storms to very arid areas with low intensities. For this analysis, IDF curves from Boulder, CO and Houston, TX are used. Peak intensities in Houston are about 40% higher than in Boulder. Thus, two cases are:

| Case | City |
|---|---|
| 1 | Boulder, CO |
| 2 | Houston, TX |

*5.2.5 Effect of assumed minimum inlet flow time*

Our preliminary simulations indicate the importance of the assumed inlet time. Inlet time should be calculated. In our case, the calculated inlet time was only 2–3 min. If this inlet time is used, then very high intensities result. The usual assumption in stormwater manuals is to use a 5 – 20 min inlet time. For the base case, a 20 min inlet time was used. Two other cases can be considered:

| Case | Inlet Time (min) |
|---|---|
| 1 | Calculated |
| 2 | 5 |
| 3 | 20 |

*5.2.6 Required minimum depth of cover*

The minimum depth of cover is a function of local climate, groundwater conditions, the presence of basements, etc. For this example, two minimum depths can be used:

| Case | Minimum Depth of Cover (ft) |
|---|---|
| 1 | 4 |
| 2 | 6 |

### *5.2.7 Effect of pipe material*

The unit cost of pipe depends on the type of material. The optimal type of pipe is a complex issue and a life cycle cost analysis should be done to decide which pipe material is better for a given location. Pipe cost information has been developed for corrugated metal pipe and reinforced concrete pipe. These two options provide two sets of scenarios.

| Case | Pipe Material |
|---|---|
| 1 | Corrugated Metal |
| 2 | Reinforced Concrete |

### *5.2.8 Possible number of scenarios*

The number of cases enumerated above are just a small percentage of the possible cases that could be considered. The combinations are listed below:

| Input Variable | Cases |
|---|---|
| Imperviousness | 2 |
| Land Use | 3 |
| Recurrence Interval | 3 |
| Climate | 2 |
| Inlet Flow Time | 3 |
| Depth of Cover | 2 |
| Pipe Material | 2 |

The number of possible combinations is the product of the above seven cases, or 432 possible scenarios, far more than we can deal with in this introductory evaluation. The selected initial five scenarios are presented below:

**Scenario 1. Boulder, CO typical**

| Input Variable | Value |
|---|---|
| Imperviousness | Present imperviousness |
| Land Use | Existing mixed land use |
| Recurrence Interval | 5 yrs |
| Climate | Boulder, CO |
| Inlet Flow Time | 20 min |
| Depth of Cover | 4 ft |
| Pipe material | RCP |

**Scenario 2. Houston, TX typical**

| Input Variable | Value |
|---|---|
| Imperviousness | Present imperviousness |
| Land Use | Existing mixed land use |
| Recurrence Interval | 5 yrs |
| Climate | Houston,TX |
| Inlet Flow Time | 20 min |
| Depth of Cover | 4 ft |
| Pipe material | RCP |

**Scenario 3. Boulder, CO major flood**

| Input Variable | Value |
|---|---|
| Imperviousness | Present imperviousness |
| Land Use | Existing mixed land use |
| Recurrence Interval | 100 yrs |
| Climate | Boulder, CO |
| Inlet Flow Time | 20 min |
| Depth of Cover | 4 ft |
| Pipe material | RCP |

**Scenario 4. Boulder, CO 5-yr storm with calculated inlet time**

| Input Variable | Value |
|---|---|
| Imperviousness | Present imperviousness |
| Land Use | Existing mixed land use |
| Recurrence Interval | 100 yrs |
| Climate | Boulder, CO |
| Inlet Flow Time | Calculated |
| Depth of Cover | 4 ft |
| Pipe material | RCP |

**Scenario 5. Boulder, CO typical with different pipe material**

| Input Variable | Value |
|---|---|
| Imperviousness | Present imperviousness |
| Land Use | Existing mixed land use |
| Recurrence Interval | 5 yrs |
| Climate | Boulder, CO |
| Inlet Flow Time | 20 min |
| Depth of Cover | 4 ft |
| Pipe material | CMP |

## 5.3 Results for the Selected Scenarios

Upon selection of the assumed scenario parameters (land use, design event, inlet time, minimum depth of cover), appropriate design variables (pipe diameter, pipe slope) are entered into the spreadsheet in a trial and error fashion. For the first scenario, a 5-yr. storm was selected from the IDF relationship for the local Boulder, CO area. The inlet flow time was assumed 20 min for all sub-basins. After these hydrologic and hydraulic assumptions were made, a feasible design was found by entering slopes and pipe diameters for each section. The feasibility of the design is established through design constraints built into the spreadsheet template (i.e., minimum pipe velocity, minimum cover depth).

The cost for this design is calculated based on the selected feasible design parameters of slope and pipe diameter. It is likely that this problem will have many feasible solutions, that can be improved upon only by further trial and error. The final cost for the first scenario is $975,000, including a geographic location factor of 92% to account for local deviation from the national average (the cost functions are based on national averages). This total is broken into pipe costs, excavation costs, bedding costs, and manhole costs in Table 5-13 and Figure 5-7.

**Table 5-13. Summary of Cost Scenarios**

| | 1. Boulder 5-Yr (1/99 $) | 2. Houston 5-Yr (1/99 $) | 3. Boulder 100-Yr (1/99 $) | 4. Boulder 5-Yr Calculated Inlet Time (1/99 $) | 5. Boulder 5-Yr With Corrugated Steel (1/99 $) | 6. Scenario 1 5-Yr With Uncertain Costs (1/99 $) |
|---|---|---|---|---|---|---|
| Total | 975,000 | 1,174,000 | 1,264,000 | 1,444,000 | 1,029,000 | 975,000 |
| Pipe | 439,000 | 556,000 | 600,000 | 749,000 | 456,000 | 439,000 |
| Excavation | 287,000 | 338,000 | 374,000 | 386,000 | 319,000 | 287,000 |
| Bedding | 161,000 | 187,000 | 193,000 | 216,000 | 163,000 | 161,000 |
| Manhole | 88,000 | 93,000 | 97,000 | 93,000 | 91,000 | 88,000 |
| | | | | | Min. Total | 538,000 |
| | | | | | Max. Total | 1,299,000 |
| | | | | | Std. Dev. | 111,000 |

Scenario 1 was then altered to reflect an identical design done for the Houston, TX area. The Houston, TX area receives approximately 80% more rainfall than Boulder, CO so the design must reflect a higher 5-yr peak flow rate. The selected feasible design for Houston, TX had steeper slopes and larger pipe diameters to convey the increased flow. This resulted in an increase of 20% over the Boulder, CO design, including the reduced location factor of 90.2% for Houston, TX. The final Houston design costs were calculated to be $1,174,000.

The rainfall intensities for the Houston, TX Scenario increased by 66% over the Boulder, CO 5-yr storm scenario. The product of length of sewer (ft) and the diameter of sewer (in.) increased by 15%, and the average slope increased 10%, from .0082 to .0090. Pipe costs increased 27%, from $439,000 to $556,000. Excavation costs increased 18%, from $287,000 in scenario 1 to $338,000 in Houston, TX.

The third scenario reflected an increased level of service for the Boulder, CO 5-yr design in Scenario 1. A 100-yr design storm was selected, resulting in a larger capacity design over the 5-yr design Boulder, CO design storm. The rainfall intensity increased 91% from the 5-yr storm to the 100-yr design storm. Consequently, the final costs increased by 30% to $1,264,000. The excavation costs increased 30% over the 5-yr design storm scenario. For the selected design, pipe costs increased 37%. The average slope of the system increased from 0.0082 to 0.098.

The fourth scenario demonstrates the dependence of the final design cost on initial hydrologic assumptions. The first three scenarios assumed a 20 min rainfall inlet time. In a basin with developed land use, the flow paths taken to the first drainage inlet may be over permeable or impervious surfaces, with widely different slopes, roughness factors, etc. For this scenario, the inlet design time was calculated based on the actual dimensions of the sub-basin, and substituted for the assumed 20 min inlet time in scenario 3. The average calculated inlet time was 10.5 min for this scenario. The altered hydrologic assumptions increased the total cost 48%, from $975,000 to $1,444,000. The majority of the cost increase was in increased pipe costs; however, a cheaper solution may exist that uses smaller pipes and steeper slopes.

The selected design also failed to meet design constraints for one pipe section. Because of a steep ground surface slope for one section, a severe slope was necessary to maintain the minimum depth of cover of 4 ft over the crown of the pipe. This severe slope caused maximum design velocities to exceed the maximum velocity constraint of 10 ft/s by 1 ft/s.

A fifth scenario was included to demonstrate the use of different pipe materials. A design using corrugated steel pipe was done for the Boulder, CO 5-yr storm. This scenario also included the increased head loss in the pipe caused by the higher roughness coefficient of the steel pipe. The Manning coefficient was increased from 0.013 for reinforced concrete pipe to 0.025 for corrugated steel pipe. This change in hydraulic performance resulted in a need for larger pipes and steeper slopes. Also, for diameters greater than 18 in. steel pipes are more expensive than concrete pipes, therefore, the final cost increased 5.5% to $1,029,000. It is likely that this design can be improved upon by further trial and error. The results of the five design scenarios are shown in Figure 5-7.

### 5.4 Effect of Uncertainty in the Estimates

Once the design is fixed, the uncertainty in the cost for that design can be estimated using Monte Carlo simulation. In this initial evaluation, we consider only uncertainty in the assumed input cost parameters since these values do not affect the final design when one is doing what-if analysis. Changes in the assumed cost would affect the design in an optimization or what's best analysis. When using risk analysis software such as @Risk or Crystal Ball, it is straightforward to introduce uncertainty into the cost estimates and then run, say 1,000 simulations to estimate the variability in the final cost estimate that is attributable to the uncertainty in the input cost estimates. In order to do Monte Carlo simulation, one needs to input a probability distribution for each input variable that is assumed to have uncertainty. For this evaluation, Scenario 1 will be used, and the

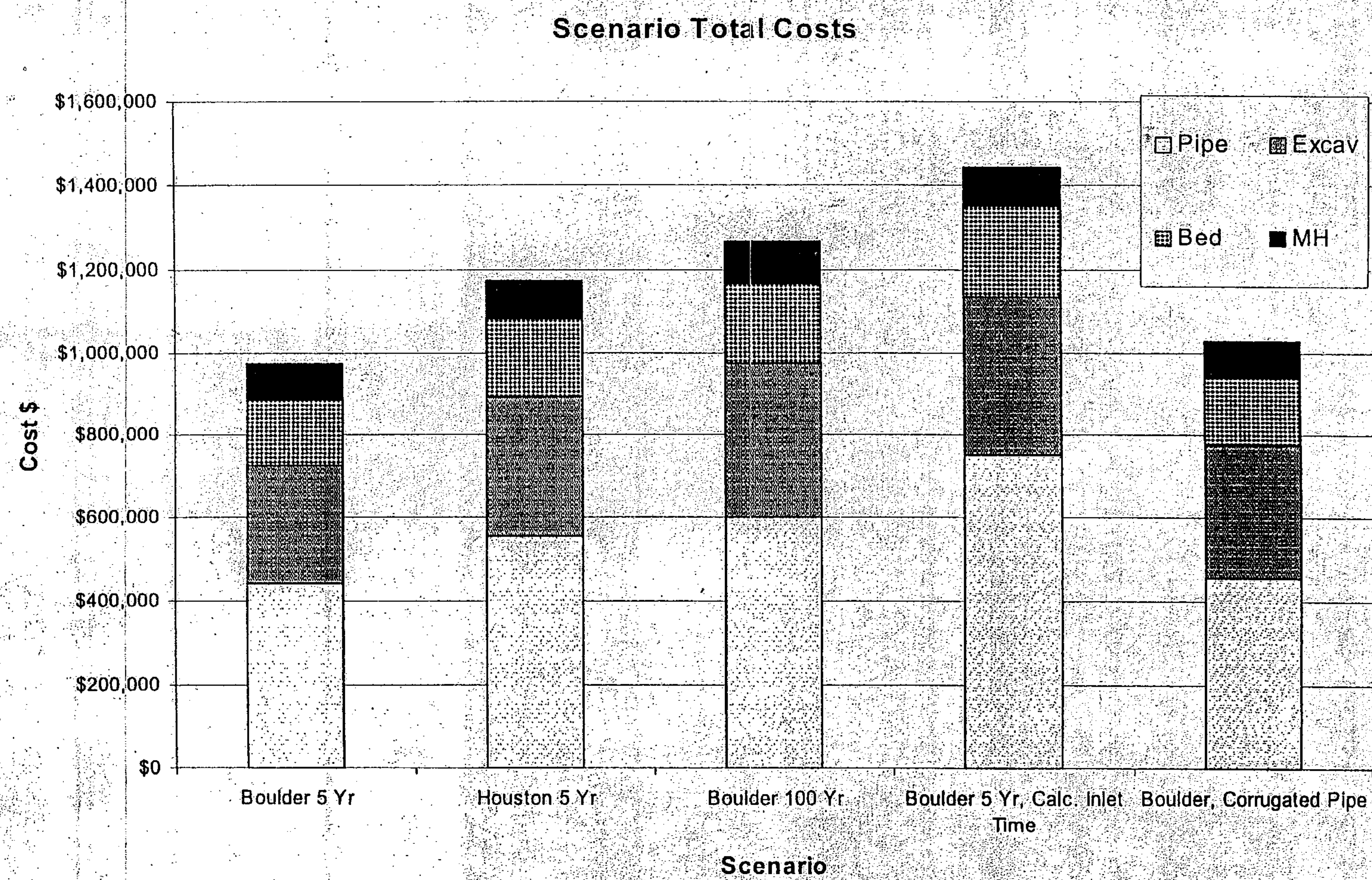



**Figure 5-7. Results of the five design scenarios.**

Pipe cost per inch diameter per foot: A normal distribution of the form, Normal (1, 0.25), is used to define a coefficient with a mean of one and standard deviation of .25. This coefficient is then multiplied by the mean pipe unit cost ($/ft). The following table shows the unit excavation cost for different type of soils:

| **Soil** | **Unit Excavation Cost (1/99 $/yd$^3$)** |
|---|---|
| Clay | Triangular* (5.67; 7.09; 8.50) |
| Sand | Triangular* (4.87; 6.12; 7.34) |
| Silt | Triangular* (5.38; 6.72; 8.06) |
| Rock | Uniform** (69; 104) |

* Triangular (minimum; mean; maximum)
**Uniform (minimum; maximum)

Monte Carlo simulation is done by repeatedly sampling from the above distributions. Each trial is a set of assumed values of the inputs. The output is the system cost for that realization. The process is repeated 1,000 times resulting in 1,000 estimates of the system cost. Finally, the cumulative distribution of these costs is determined and the results reported. Monte Carlo simulation allows us to see how uncertainty in inputs affects the final answer. It is assumed that there is no covariance between the variables.

The minimum cost recorded in the 1,000 Monte Carlo simulations was $538,000 and the maximum was $1,299,000. The mean cost of $974,867 compared well with the cost of scenario 1, $975,000. The standard deviation of the 1,000 simulation results was $111,000. The cumulative distribution of total costs is shown in Figure 5-8. The source of the variance is shown in a tornado plot depicted in Figure 5-9. The majority of the uncertainty in the final cost is due to the uncertainty assumed for the pipe costs, despite being a smaller fraction of the total costs.

### 5.5 Summary and Conclusions on Scenarios

The results of the five scenarios and the uncertainty analysis are shown in Table 5-13. The effect of design assumptions and initial conditions on the final outcome of the design is evident. However, hidden within these what-if analyses is the fact that the selected designs are merely one feasible solution of the many possible designs that satisfy the design constraints. When a design assumption was changed, say from the 5-yr event in scenario 1 to the 100-yr event in scenario 3, the physical design was altered greatly to convey the added flowrate. It is possible that a nearly optimal solution is compared against a sub-optimal solution in Table 5-13. Therefore, direct comparisons of design costs are impossible. While valuable, the what-if analysis does little to illuminate the optimal solution.

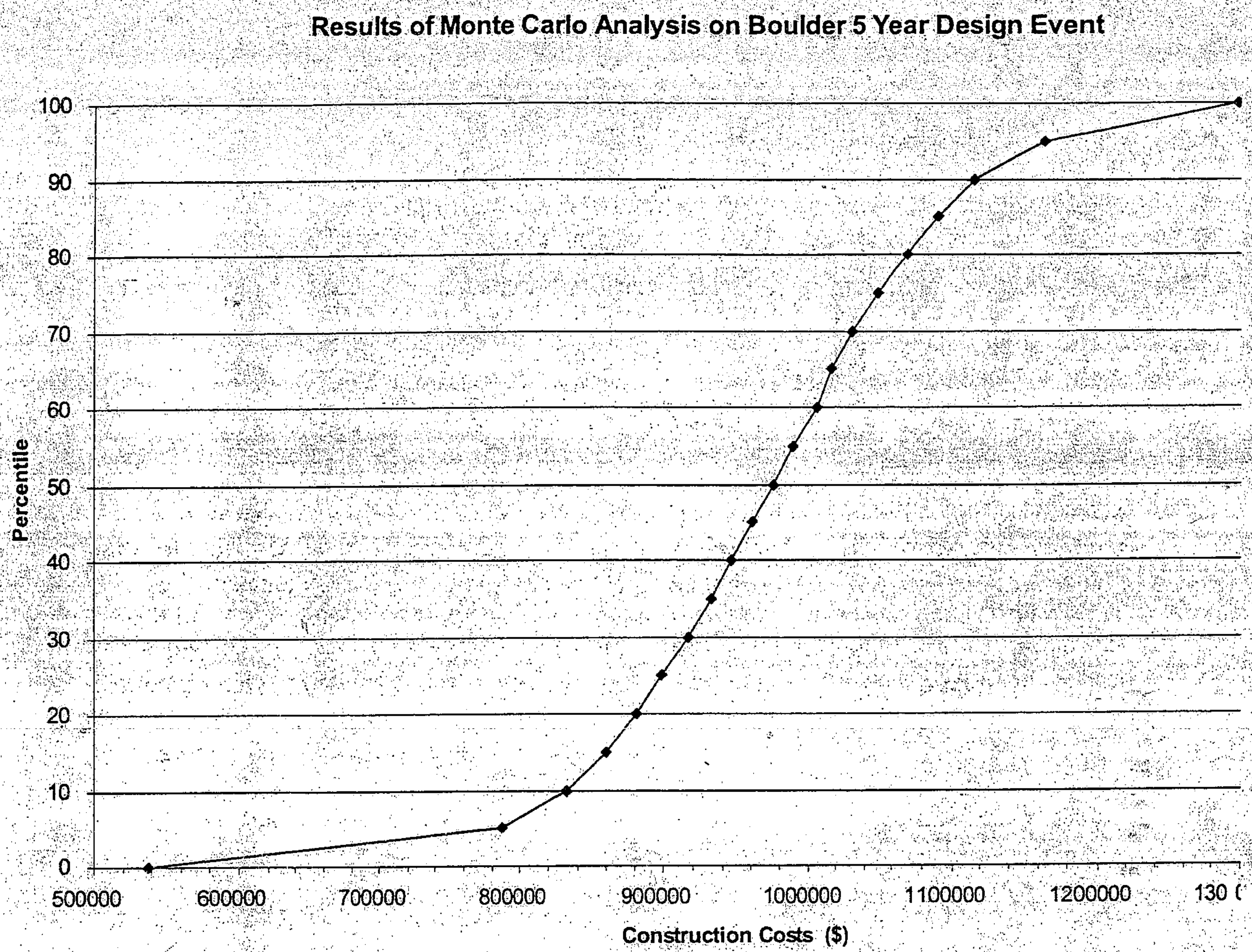



Figure 5-8. Cumulative total cost distribution

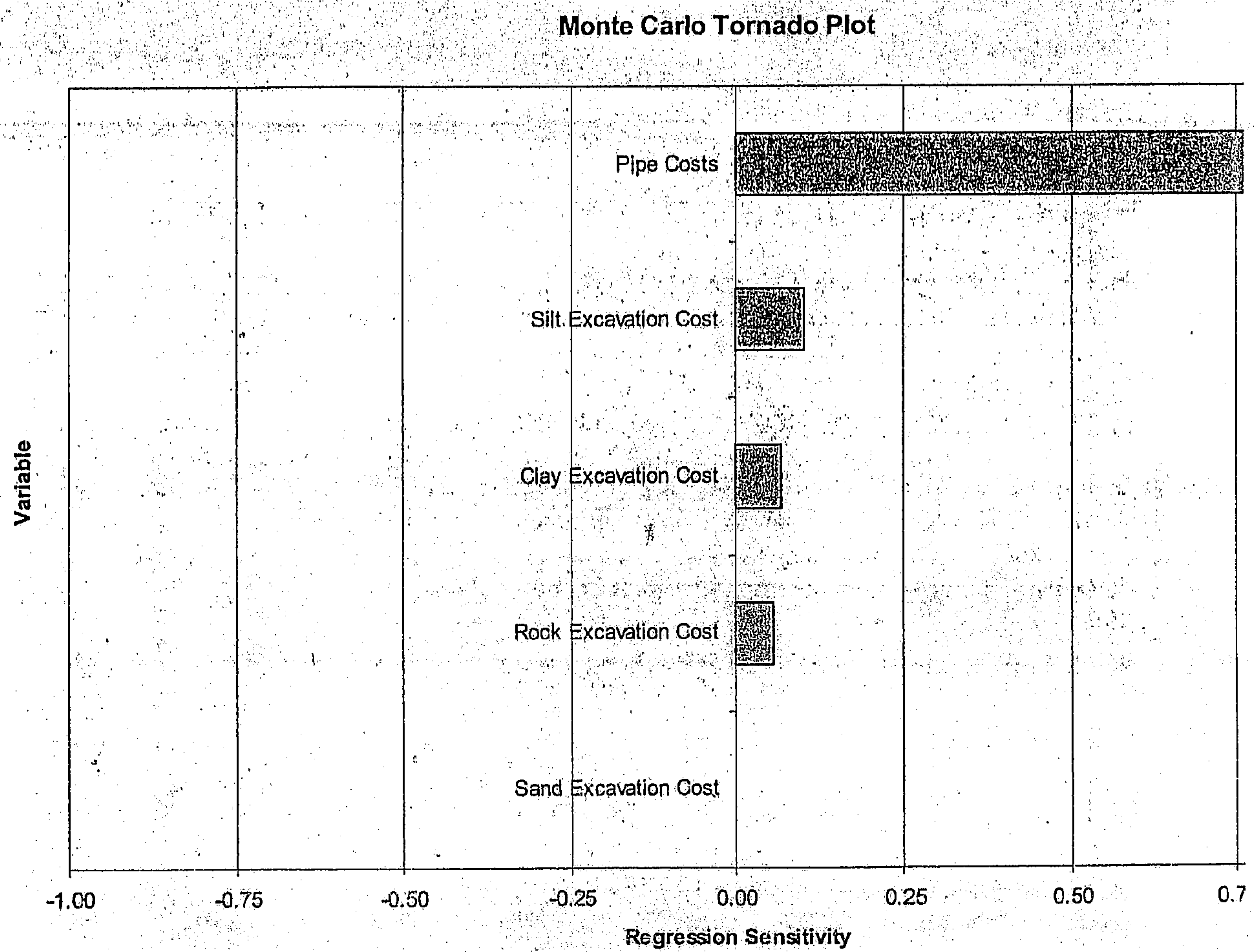



**Figure 5-9. Tornado plot of uncertainty in scenario.**

A more robust comparison of design costs would include optimization techniques to find optimal designs for each scenario. Then the true costs of increasing the level of service from a 5-yr storm to a 100-yr storm could be measured. To illustrate this point, assume that the design selected for Scenario 1 is very nearly optimal and the design for Scenario 3 is grossly over designed. For illustrative purposes, assume that the optimal design for the 100-yr storm in Scenario 3 is $1,000,000, and that the increased benefit from flood damage is estimated to be $250,000. That is, an estimated $250,000 will be saved over the life of the project if the drainage system is designed for a 100-yr event instead of only a 5-yr event. Under the designs found in Scenarios 1 and 3, the increased level of service ($1,264,000 – $975,000 = $289,000) would not be warranted because the costs of the increased project exceed the estimated benefits ($250,000). However, if optimal solutions were to be found for each scenario, the increased level of service in Scenario 3 would be worthwhile, because the costs of increasing the level of service from Scenario 1 to Scenario 3 ($1,000,000 – $975,000 = $25,000) would be exceeded by the expected increase in benefits ($250,000). While the example is simplified by the exclusion here of such variables as possible increased maintenance costs and uncertainty in increased benefits, it does illustrate the importance of obtaining optimal design solutions to enable direct comparison among alternatives.

## Chapter 6

# Cost-Effectiveness of Alternative Micro-storm Management Options

## 6.1 Introduction

In a recently completed project sponsored by the U.S. Environmental Protection Agency titled *Innovative Urban Wet-Weather Flow Management Systems* (Heaney et al., 1999a), many methods for improving urban stormwater quality were described. Approaches range from traditional end-of-pipe treatment methods, to sophisticated source control BMPs, including land use controls. A summary of many of these approaches is presented by Heaney et al. (1999b). However, innovative wet weather flow (WWF) quality management programs must be designed in concert with the need to provide adequate flood protection and drainage. Interestingly, innovative methods for flood control and drainage focus similarly on source controls and non-structural options (Heaney et al., 1998c). The resulting new paradigm for WWF management is that the analyst will need to evaluate a very large variety of management options that include land use modifications. Fundamental questions arise regarding how to develop effective methods for the evaluation of alternatives and how to prioritize among them. In one report, Heaney et al. (1998c) describe the optimization methods used to prioritize among options, While in another (Heaney et al., 1999b) they evaluates the role of geographical information systems (GIS) in providing the essential spatial information for these new approaches. The interested reader is referred to the other cited reports for a more complete description of these other aspects.

In this section we describe some preliminary results in developing cost estimates for land-intensive BMP urban stormwater control systems. Developing reliable cost estimates is also complicated because many BMPs are designed to serve multiple purposes. For example, if the yard of a house is retrofitted to replace one half of the lawn with infiltration and wooded areas, does the homeowner perceive a loss of the use of this yard, or welcome the fact that there will be less lawn to maintain? Controls for stormwater quality management using micro-storm (i.e., storms of a low return period of say, two months) design criteria also have value for larger design storms for drainage and flood control. Thus, these costs need to be allocated among purposes. A robust solution is one that works well over the entire spectrum of future scenarios. Traditional stormwater management systems have been designed to function well under a single design condition, e.g., the 100-yr flood (major storm) or the 10-yr storm (minor storm). Unfortunately, designing a control systems around a single extreme event is myopic because the design may not perform well under other scenarios. Major floodways designed for the 100-yr event degrade the natural stream system, overdrain the system during more frequent storms, and degrade downstream water quality by transporting pollutants rapidly through urban areas. Concern for water quality and receiving stream integrity in urban stormwater systems demonstrates the importance of a stormwater system that performs well in managing the runoff from frequent, or "micro" storms that occur on a regular basis, e.g., weekly or monthly. Lippai and Heaney (1998) present principles for doing cost allocations across purposes (micro, minor, and major storms) and groups (residential, commercial, transportation, etc.) for water supply systems. The same principles can be applied to stormwater systems. What is needed for WWF systems is an efficient method for optimizing stormwater control systems for micro to major storms. The companion report by Heaney et al. (1998c) shows how this can be done for simpler cases. More research is needed to develop fully functional models for more realistic scenarios.

Below we review previous efforts to evaluate micro-storm systems, present methods for estimating the unit costs of these BMPs, and display the results of using these cost estimates for finding the optimal mix of BMPs.

## 6.2 Literature Review

Pitt (1987) showed the importance of evaluating smaller storms with regard to urban stormwater quality protection. He initiated the development of the Source Loading and Management Model (SLAMM) used to estimate the efficacy of various urban nonpoint source water quality management options (Pitt and Voorhees, 1995). SLAMM emphasizes small storm hydrology and its associated particulate washoff. The predictive equations in SLAMM are based on extensive field data. Below is a brief description of the relevant components of SLAMM.

### *6.2.1 Land use/control options*

SLAMM depicts urban land use as falling into the following major categories:

1. Residential Areas
2. Institutional Areas
3. Commercial Areas
4. Industrial Areas
5. Open Space Areas
6. Freeways

The first five of these areas contain up to the 14 source area types shown in Table 6-1.

The area in acres is needed for each of these source areas. Finally, the additional information shown in Table 6-2 is needed for some of the source areas.

Table 6-1. Source Areas in SLAMM (Pitt and Voorhees 1995)

| Source Area | Number Available in Each Land Use |
|---|---|
| Roofs | 5 |
| Paved Parking/Storage | 3 |
| Unpaved Parking/Storage | 2 |
| Playgrounds | 2 |
| Driveways | 3 |
| Sidewalks | 2 |
| Street Areas/Alleys | 3 |
| Large Landscaped Areas | 2 |
| Undeveloped Areas | 1 |
| Small Landscaped Areas | 3 |
| Isolated Areas | 1 |
| Other Permeable Area | 1 |
| Other Directly Connected Impervious Area | 1 |
| Other Partially Connected Impervious Area | 1 |
| Paved Freeway and Shoulder Area (F)* | 5 |
| Large Turf Area (F)* | 1 |

* (F) indicates available in Freeway Land Use only

Table 6-2. Other Information Needed in a Source Area (Pitt and Voorhees 1995)

| |
|---|
| Type of roof-pitched or flat |
| Source area connectedness-unconnected or draining to a permeable area. |
| Soil type-sandy (A/B) or Clayey (C/D). |
| Building density – low or medium/high |
| Pavement of alleys – yes or no |
| Pavement texture – smooth to very rough |
| Total street length – curb miles |
| Street dirt accumulation equation coefficients |
| Initial street dirt loading |
| Average daily traffic – vehicles/day |

While SLAMM uses far more detail and represents a significant improvement over other stormwater models, it still uses a highly aggregate representation of soil and land use conditions, e.g., only two soil classifications are used, building densities are either low or medium/high. An example printout of the input file for an analysis in Toronto, shown in Table 6-3, gives a general idea of the amount of spatial aggregation. Thirty source area categories are shown, 12 of which have positive amounts of acreage. Small landscaped areas account for 436 out of a total of 730 acres

Table 6-3. Sample SLAMM Output for Toronto, ON, Canada (Pitt and Voorhees, 1995)
(Reproduced with permission of Dr. Robert Pitt)

```
Data file name:  EXAMPL3.DAT
Rain file name:  LN80.RAN                                   Particulate Solids Concentration file name:  TORONTO.PSC
Runoff Coefficient file name:  RUNOFF.RSV                   Pollutant Relative Concentration file name:  TORONTO.POL
Study period starting date:  04/10/80                       Study period ending date:  04/30/80
Date:  04-07-1989                                           Time:  06:51:55
Site information:  WET POND WITH STANDARD CONTROLS
```

Areas for each Source (acres)

| Source Area | Resi-dential Areas | Institu-tional Areas | Commercial Areas | Industrial Areas | Open Spaces Areas |
|---|---|---|---|---|---|
| Roofs 1 | 53.20 | 0.00 | 0.00 | 0.00 | 0.00 |
| Roofs 2 | 41.56 | 0.00 | 0.00 | 0.00 | 0.00 |
| Roofs 3 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Roofs 4 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Roofs 5 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Paved Parking/Storage | 1.52 | 0.00 | 0.00 | 0.00 | 0.00 |
| Paved Parking/Storage | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Paved Parking/Storage | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Unpaved Parking/Storag | 0.76 | 0.00 | 0.00 | 0.00 | 0.00 |
| Unpaved Parking/Storag | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Playground 1 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Playground 2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Driveways 1 | 28.12 | 0.00 | 0.00 | 0.00 | 0.00 |
| Driveways 2 | 25.12 | 0.00 | 0.00 | 0.00 | 0.00 |
| Driveways 3 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Sidewalks/Walks 1 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Sidewalks/Walks 2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Street Area 1 | 28.88 | 0.00 | 0.00 | 0.00 | 0.00 |
| Street Area 2 | 58.52 | 0.00 | 0.00 | 0.00 | 0.00 |
| Street Area 3 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Lrg Lndscpd Area 1 | 1.52 | 0.00 | 0.00 | 0.00 | 0.00 |
| Lrg Lndscpd Area 2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Undeveloped Area | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Smll Lndscpd Area 1 | 435.24 | 0.00 | 0.00 | 0.00 | 0.00 |
| Smll Lndscpd Area 2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Smll Lndscpd Area 3 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Isolated Area | 1.52 | 0.00 | 0.00 | 0.00 | 0.00 |
| Other Pervious Area | 30.40 | 0.00 | 0.00 | 0.00 | 0.00 |
| Other Directly Connect | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Other Partially Connec | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Total | 730.35 | 0.00 | 0.00 | 0.00 | 0.00 |

| Freeway Source Area | Area (acres) |
|---|---|
| Paved Lane & Shoulder Area 1 | 0.00 |
| Paved Lane & Shoulder Area 2 | 0.00 |
| Paved Lane & Shoulder Area 3 | 0.00 |
| Paved Lane & Shoulder Area 4 | 0.00 |
| Paved Lane & Shoulder Area 5 | 0.00 |
| Large Turf Areas | 0.00 |
| Undeveloped Areas | 0.00 |
| Other Pervious Areas | 0.00 |
| Other Directly Connected Imperv Area | 0.00 |
| Other Partially Connected Imperv Area | 0.00 |
| Total | 0.00 |

### *6.2.2 Hydrology in SLAMM*

Using field measurements, a rainfall-runoff relationship is established for the study area. Such a relationship for clean, rough streets is shown in Figure 6-1. The 45° line represents a 1:1 rainfall-runoff relationship. Losses can be partitioned as follows:

1. Initial losses, also known as initial abstraction, and
2. Maximum variable losses.

Three stages of rainfall-runoff response can be identified:

1. The amount of rainfall before any runoff is produced.
2. The rainfall range between no runoff and all of the losses being satisfied, the nonlinear portion of the runoff curve.
3. The rainfall beyond stages 1and 2, wherein the rainfall and runoff rates are equal.

Our main concern for water quality is with stages 1 and 2. Urbanization reduces the initial abstraction. It also tends to reduce the total infiltration since the infiltration capacity has been reduced by development.

### *6.2.3 NRCS method and initial abstraction*

Pitt (1987) provided an excellent review of the literature on the nature of the initial abstraction. Initial abstraction includes the following:

- Detention storage, e.g., on flat roofs
- Infiltration into the soil
- Interception by vegetation, particularly trees
- Evaporation from impervious surfaces such as streets.

Recognizing the uncertainty of the estimates of the total initial abstraction, we will use this concept to illustrate our methodology.

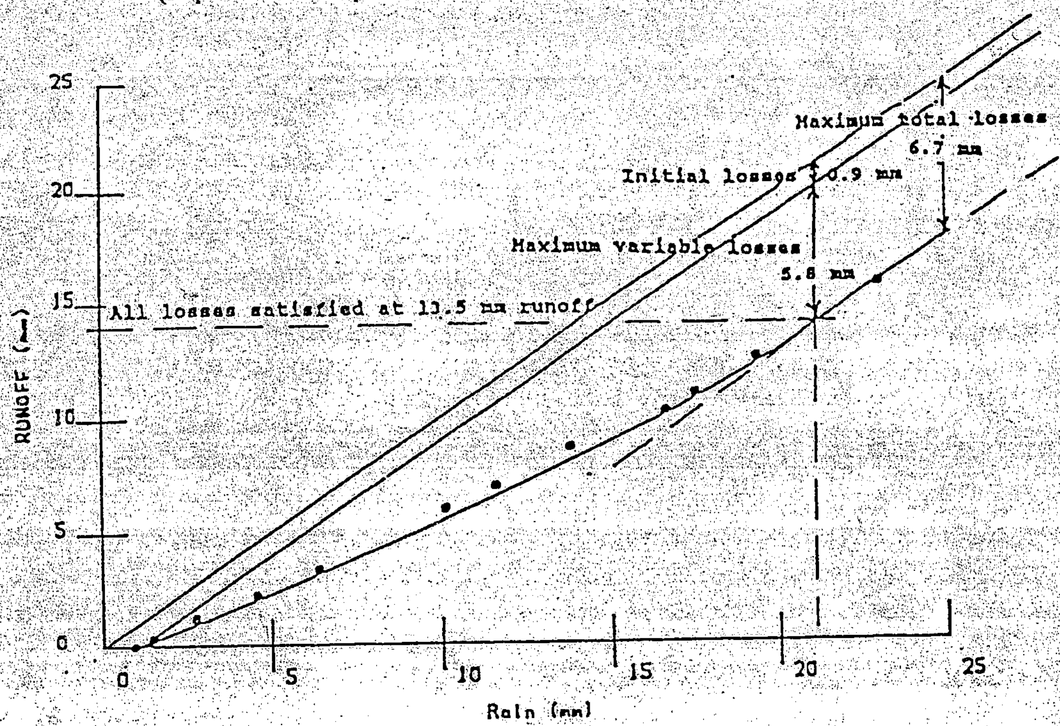
### *6.2.4 Costs of controls in Pitt's work*

Pitt (1987) estimated the following costs (as 1986 Canadian $) and needed to be revised.

- Street cleaning: $50 per curb-km cleaned
- Catchbasin cleaning: $50 per catchbasin cleaned
- Redirecting roof drains to permeable areas: $125 per house
- Infiltration trenches: $40,000 per ha paved area or roof
- Detention ponds: $200,000 per ha pond surface

  Annual maintenance costs are 4% of initial construction costs

**Figure 6-1. Illustrative rainfall-runoff relationship (Pitt, 1987).**
**(Reproduced with permission of Dr. Robert Pitt)**



### *6.2.5 Control devices in SLAMM*

SLAMM evaluates the following control devices (Pitt and Voorhees, 1995):

- Wet detention ponds
- Porous pavement
- Infiltration devices
- Other devices for source areas
- Street cleaning
- Catchbasin cleaning
- Grass swales
- Other outfall devices

### *6.2.6 Limitations of SLAMM*

SLAMM is an improvement over other approaches that neglect the dynamics of small storms. It also uses more refined spatial information and breaks land uses down into functional units, or source areas. However, its cost evaluation is limited and has not been updated since 1987. More importantly, it only does what-if analysis and cannot be used to find optimal solutions.

### *6.2.7 Low impact development*

Some design guidelines are available for micro-storms. Extensive work has been done by Prince George's County (1999) Maryland to develop designs for Low Impact Development. They use the Natural Resources Conservation Service (NRCS) Curve Number (CN) approach to evaluate the percentage of the development that must be set aside in order to provide storage. Other design guidelines suggest capturing the first part of the runoff, typically the first 0.5 to 1 in. of runoff.

## 6.3 Proposed Approach

### *6.3.1 Introduction*

Heaney et al. (1998c) describe a proposed method for using the NRCS CN method for evaluating micro-storms. The fundamental principle for the proposed approach is that development should not reduce the initial soil moisture storage that existed prior to development. This initial soil moisture storage is equivalent to the initial abstraction as calculated using the NRCS CN method. The initial abstraction is a good measure of the ability of the soil system to filter the stormwater. The initial abstraction, as a function of CN, is shown in Table 6-4. Inspection of Table 6-4 reveals the importance of CN. A low CN of 30 corresponds to an initial abstraction of 4.67 in. Even at a CN of 80, the initial abstraction is still 0.5 in. If the original CN is fairly low, then a significant amount of soil moisture storage is lost if this area is rendered impervious by development.

**Table 6-4. Initial Abstraction as a Function of Curve Numbers (CN)**

| CN | $I_a$ (in.) | CN | $I_a$ (in.) |
|---|---|---|---|
| 20 | 8 | 70 | 0.86 |
| 30 | 4.67 | 80 | 0.5 |
| 40 | 3 | 90 | 0.22 |
| 50 | 2 | 100 | 0.02 |
| 60 | 1.33 | | |

**Note: Ia = initial abstraction**

The method presented here uses the concept of modifying the CN for the developed condition so that the modified CN is the same as the natural CN. The more cost-effective controls tend to focus on using the permeable area for more intensive infiltration. Alternatively, we seek to design hydrologically functional landscapes as described in the next section.

### *6.3.2 Hydrologically functional landscaping*

Traditional landscaping relies on covering most, if not all, of the permeable area with grass. The lot is graded so that stormwater drains to the street and/or the rear of the lot as shown in Figure 6-2 (Dewberry and Davis, 1996). An example of a hydrologically functional landscape is shown in Figure 6-3 (Prince George's County, 1999). The general idea is to maximize the infiltration of stormwater by providing depressions, draining runoff from impervious areas to permeable areas, providing more circuitous routes for the stormwater to increase the time of concentration.

### *6.3.3 Cost of CN modifications*

If the cost of modifying the CN can be determined, then cost-effective strategies can be developed for maintaining the undeveloped CN for each parcel or combination of parcels. Most BMPs are land intensive. Thus, if a BMP is installed within a right-of-way, or in a backyard, or in open space land, should the cost of the land be included in the calculation? What is the value of this land? This important topic is discussed below.

### *6.3.4 Land valuation*

Land valuation is of critical importance for many controls because it constitutes a significant, if not major, component of total costs. Traditional urban storm drainage designs relied on subsurface sewer systems to carry WWF from the service area. Thus, land costs were not an important factor because no land was used in the process. However, once requirements for detention and retention systems were included in the WWF designs, then the cost of the land became an issue. Various perspectives on the cost of land are summarized below:

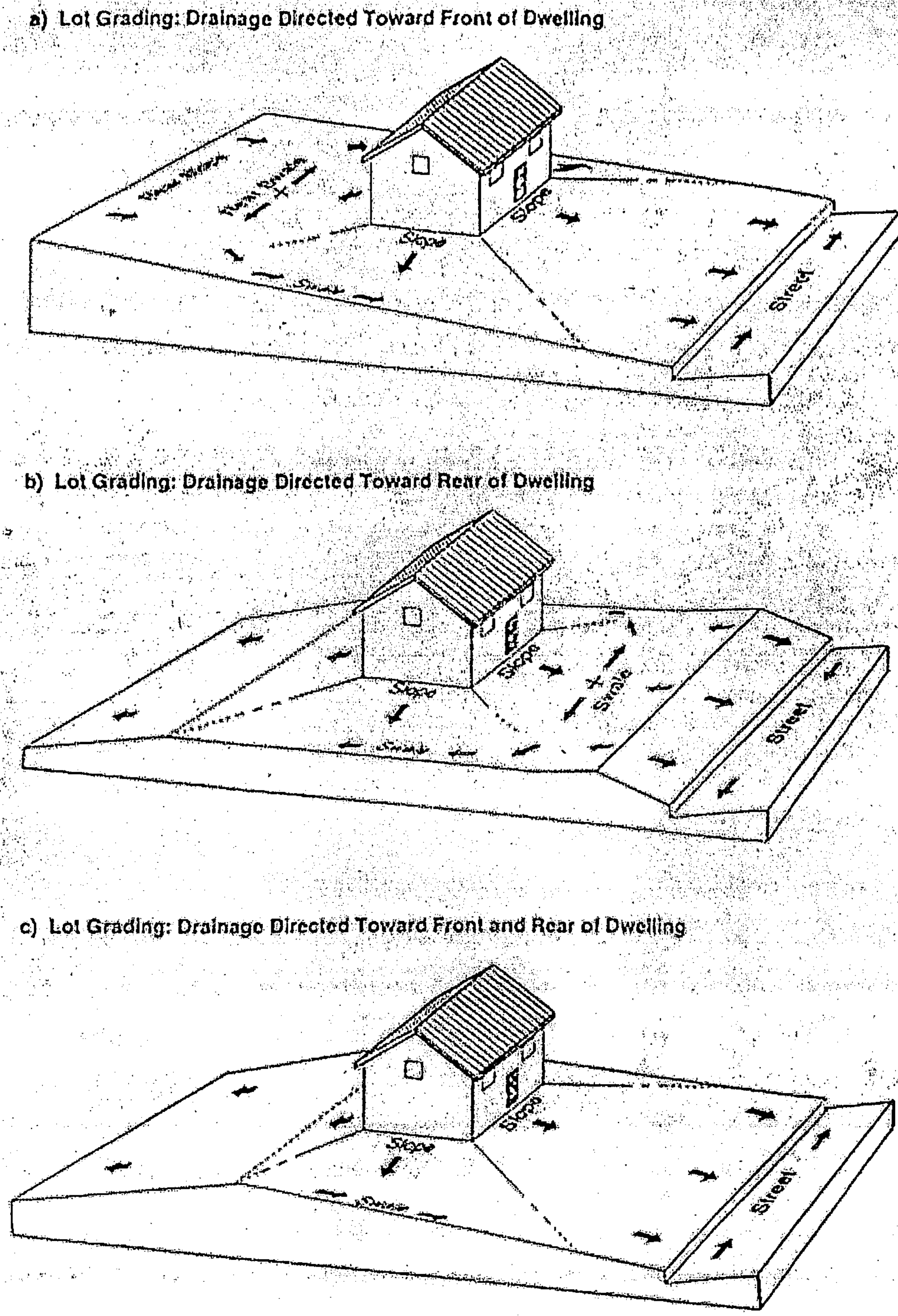



Figure 6-2. Conventional storm drainage (Dewberry and Davis, 1996).
(Reproduced with permission of The McGraw-Hill Companies)

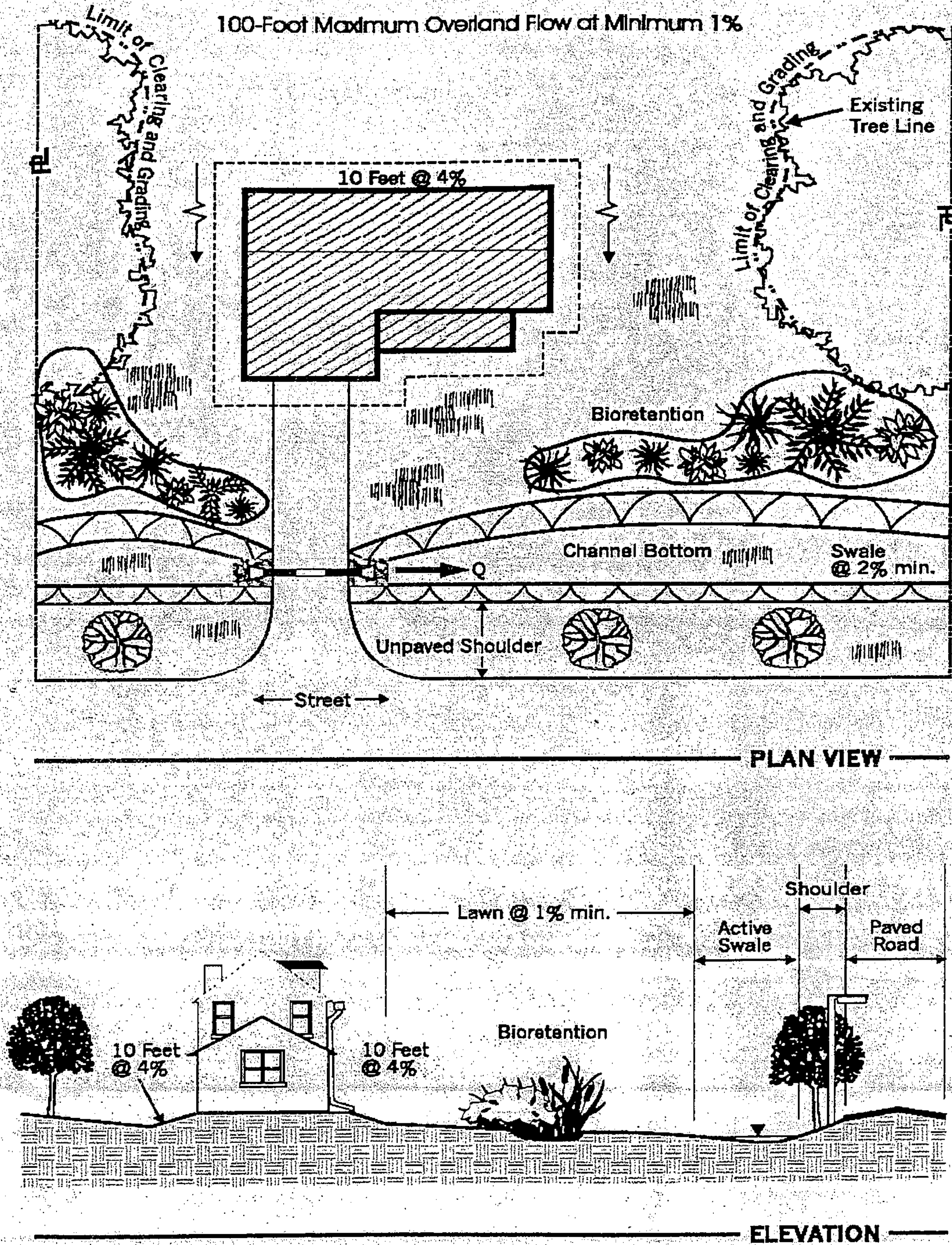



Figure 6-3. Illustration of hydrologically functional landscape (Prince George's County, 1999) (Reproduced with permission of the Prince George's County).

- The land should be valued at zero because it is part of the required right-of-way that the developer must provide along with the traditional right-of-way for streets and sidewalks, schools, and parks. If the land is on private property and is being used as landscaping, then it is viewed as being free for this other purpose.
- The land should be valued at full market value since the developer would otherwise be able to use this land for additional development of houses, commercial development, and/or other uses.

This issue is of paramount importance in estimating the "true cost" of land-intensive urban WWF BMPs whether they are located onsite or offsite. While little literature is available on this subject for urban stormwater systems, this topic has been discussed extensively with regard to evaluating the cost of transportation systems. This related literature is reviewed in the next section.

6.3.4.1 Value of land for transportation

A relatively large body of literature exists that is directed at estimating the true costs of various forms of transportation, particularly automobile-related transportation. Litman (1998) summarizes this literature and recommends methods for properly estimating the cost of transportation. Heaney et al. (1999a) quantify the impact of the automobile on urban land use in general and urban stormwater systems in particular. Accommodating the automobile requires committing a major portion of contemporary urban systems for such constructs as streets, driveways, parking lots, and garages. Some of the cost of providing land for transportation is paid by external subsidies from the state and federal governments. Much of the cost of local street and parking systems are paid by property and sales taxes. Thus, virtually none of these costs are directly assessed on the user. This approach is in stark contrast to a water utility wherein the total cost is assigned to the users, much of it in the form of commodity charges, so that they are aware of the full cost and have direct incentives to reduce their demand. For the purposes of this section, assume that a transportation utility exists in the urban area. This utility is responsible for all aspects of transportation and parking. It must pay full cost for its network, and it levies this cost directly on the transportation users. Litman (1998) defines roadway land value as follows:

*Roadway land value costs include the value of land used for rights-of-way and other public facilities dedicated for automobile use. This cost could also be defined as the rent that users would pay for roadway land if it were managed as a utility, or at a minimum, the taxes that would be paid if road rights-of-way were taxed.*

**6.3.4.2 Rate of return on land investments**

Real estate appraisers estimate market value, which can be defined as (Boyce 1981):

*The highest price in terms of money which a property will bring in a competitive and open market under all conditions requisite in a fair sale, to the buyer and seller each acting prudently, knowledgeably, and assuming the price is not affected by undue stimulus.*

The present value of a series of future annual income is:

$$PV = A\left[\frac{1-(1+i)^{-n}}{i}\right] \tag{6-1}$$

Where

$PV$ = present value, \$
$A$ = annual income, \$/yr
$n$ = number of yrs
$i$ = annual interest rate

As $n$ tends to infinity, equation 6.1 becomes capitalized present value of an infinite stream of future benefits ($PVC$):

$$PVC = \frac{A}{i} \tag{6-2}$$

The present value of an infinite future stream of earnings is called the capitalized value of the future income stream. For example, a detailed investigation of the rate of return for muck farms north of Lake Apopka in Florida revealed an expected annual return of about $460/acre (Heaney et al. 1998d). Using a discount rate of 10%, the expected value of this land would be $4,600/acre. Detailed studies of comparable muck farmland indicated an average selling price of $4,500/acre, very close to the farm budget analysis.

For urban land use, there is no similar simple metric of land value in terms of crop productivity. However, a reliable estimate of the value of urban land can be obtained by viewing the urban development as an investment opportunity. The first step is to calculate the investment in raw land and its improvements exclusive of the building. Then, a reasonable return on investment, say 8%, is assumed. Thus, the annual benefit of committing this parcel of land to this use is 8% of the investment. The land is assumed to hold its value over time. Thus, the present value of the future sales price equals the original purchase price. Then, the cost of committing land to this use is the opportunity cost as estimated as the investment cost times the rate of return.

It is instructive to trace the development of raw land into housing or other uses, and then estimate the investment in raw and improved land. Dion (1993) provides a breakdown on the components of cost for a typical house built in 1992 as shown in Table 6-5. Finished land and labor/materials constitute 73% of the total cost. If the overhead and financing are prorated to the land and the house then the land cost constitutes about 27% of total cost, or 38% of construction costs.

**Table 6-5. Breakdown of the Cost of a Typical House (Dion 1993)**

| Item | % of Total | Cost ($) |
|---|---|---|
| Overhead | 20 | 24,000 |
| Financing | 5 | 6,000 |
| Finished land | 20 | 24,000 |
| Labor/materials | 53 | 63,600 |
| Total | 98 | 120,000 |

The Urban Land Institute (1989) presents another breakdown of land development costs for 1984 and 1988 as shown in Table 6-6. For 1988, land costs are about 76% of construction costs while they are 51% of construction costs in 1984. A rule of thumb in the home construction industry is that the house costs should be about twice the land costs. Thus, we will use land costs to be 50% of construction costs.

**Table 6-6. Breakdown of the Cost of Housing in 1984 and 1988 (Urban Land Institute 1989)**

| Item | % of development (1988 $) | % of development (1984 $) |
|---|---|---|
| Raw land | 19.3 | 17 |
| Land improvements | 12.6 | 7 |
| Financing | 4.4 | 6 |
| Labor | 17.4 | 18 |
| Marketing | 4.3 | 4 |
| Materials | 24.1 | 29 |
| Overhead | 6.5 | 7 |
| Profit | 8.1 | 9 |
| Advertising | 1.2 | 2 |
| Other | 0.4 | 2 |
| Total | 98.3 | 101 |

**Note: The totals do not sum to 100 in the source**

A breakdown of housing costs by function for a typical house is shown in Table 6-7. The total construction cost for the house is about $118,200. The total land value is estimated to be 50% of the cost of the house. Each component is then allocated its value based upon the proportion of area that it occupies. Unimproved land is assumed to be 2/3 of the total land value. The costs of improvements for water, wastewater, and stormwater are estimated for each functional unit. For example, all of the wastewater costs are assigned to the house. The result is a total land value attributable to the yard of $29,702. The capital and operation and maintenance costs for the yard are shown in Table 6-7. Capital costs consist of the initial preparation of topsoil plus landscaping, typically sod. Also, a sprinkler system is included. This option can be dropped as appropriate. Operation and maintenance costs consist of irrigation water, maintenance of the yard and the sprinkler system, and the opportunity cost of the land. The total present value of these costs is $87,880 or $6.76 per ft$^2$ of yard area.

Table 6-7. Estimated Housing Costs

| Component | Area ($ft^2$) | % of total | Cost ($\$/ft^2$) | Construction Cost (1/99 $) | Total Land Cost (1/99 $) | Unimproved Land Cost (1/99 $) |
|---|---|---|---|---|---|---|
| Roof-house | 1600 | 12.3% | 56.25 | 90,000 | 7,274 | 4,849 |
| Roof-garage | 400 | 3.1% | 34.00 | 13,600 | 1,818 | 1,212 |
| Driveway | 800 | 6.2% | 4.00 | 3,200 | 3,637 | 2,425 |
| Yard | 9800 | 75.4% | 1.00 | 9,800 | 44,552 | 29,702 |
| Patio | 400 | 3.1% | 4.00 | 1,600 | 1,818 | 1,212 |
| Total | 13000 | 100.0% | | 118,200 | 59,100 | 39,400 |

| Item | Input Data | Good (1/99 $\$/ft^2$) | Fair (1/99 $\$/ft^2$) | Poor (1/99 $\$/ft^2$) |
|---|---|---|---|---|
| **A. Initial Capital Investment** | | | | |
| 1. Soil preparation | | | | |
| Initial cost of sod | | 0.43 | 0.34 | 0.26 |
| Initial cost of topsoil, 6 in. | | 0.50 | 0.40 | 0.30 |
| Spreading topsoil, 6 in. | | 0.64 | 0.51 | 0.38 |
| Soil conditioners | | 0.03 | 0.02 | 0.01 |
| Sprinkler system | | 0.62 | 0.44 | 0.00 |
| | | 2.22 | 1.71 | 0.95 |
| 2. Opportunity Cost of Land | | | | |
| Land Investment Cost, $ | 44,552 | | | |
| Opportunity cost investment rate | 6% | | | |
| Annual cost, $/yr | 2,673 | | | |
| Interest rate per yr | 0.06 | | | |
| Present worth over 25 yr, $ | 34,172 | | | |
| Cost in $\$/ft^2$ | | 3.49 | 3.49 | 3.49 |
| Total of initial capital investment | | 5.71 | 5.20 | 4.44 |
| **B. Operation & Maintenance Costs, $** | | | | |
| Lawn watering | | | | |
| In./yr | 20 | | | |
| % of permeable area that is irrigated | 80% | | | |
| Cost of water, $/1,000 gal. | 1.50 | | | |
| Present worth factor | 12.78 | | | |
| Present worth, $\$/ft^2$ | | 0.24 | 0.15 | 0.09 |
| Lawn maintenance | | | | |
| Weeks/yr. | 26 | | | |
| $/week | 17 | | | |
| Maintenance area, $ft^2$ | 7840 | | | |
| Present worth, $\$/ft^2$ | | 0.72 | 0.50 | 0.35 |
| Sprinkler system maintenance | | 0.25 | 0.15 | 0.00 |
| Total operation and maintenance costs, $ | | 1.21 | 0.80 | 0.44 |
| **C. Total Cost, $\$/ft^2$** | | 6.92 | 6.00 | 4.88 |
| **Portion attributable to stormwater** | | | | |
| Assumed % | 10% | | | |
| **D. Cost for Stormwater** | | 0.69 | 0.60 | 0.49 |

6.3.4.3 Value of land for WWF systems

We support the view that land value should be included in the cost of WWF systems. The amount to be charged should be based on the opportunity cost of this land. This charge is an essential part of the analysis because most of the onsite or neighborhood BMPs are land intensive, e.g., detention systems, functional landscapes. The incidence of these costs is also critical in order to reward customers for onsite controls and to properly assess all users for their fair share of the total cost.

6.3.4.4 Customers in the WWF system

The customers of the urban WWF system can be viewed as the individual parcels served by the system. However, this taxonomy ignores perhaps the largest generator of urban WWFs, especially during micro-storms. This large customer is transportation that takes place in the rights-of-way of cities. This right-of-way consists of about 25% of total land use. However, it constitutes a disproportionately large amount of the directly connected impervious area that is critical in reducing the natural initial abstraction. Transportation systems also constitute a major portion of the WWF quality loads. Thus, they should be included as separate customers in order to evaluate their share of the cost of the WWF system.

## 6.4 Hypothetical Study Area

The study area shown in Figure 5-3 was digitized, and a parcel level GIS developed based upon each graphic object. The available themes are the following:

1. Land Use
2. Parcels
3. Storm Sewer Lines
4. Manholes
5. Soils
6. Spot Elevations
7. Street Right-of-way
8. Rooflines
9. Driveways

The study area GIS is shown in Figure 6-4. The land use classifications of the study area are shown in shaded colors. Rights of way are shown in shaded blue, rooflines are outlined in purple, driveways are in solid magenta, the storm sewer system is outlined in red, manholes for the storm sewers are in solid black, and the parcel boundaries are in black outline.

A representation of the soils for the site is shown in Figure 6-5. The three soil classifications are shown as green for rock, light brown for clay, and dark brown for silt. The soil classification is based upon the values given in Table 5-8.

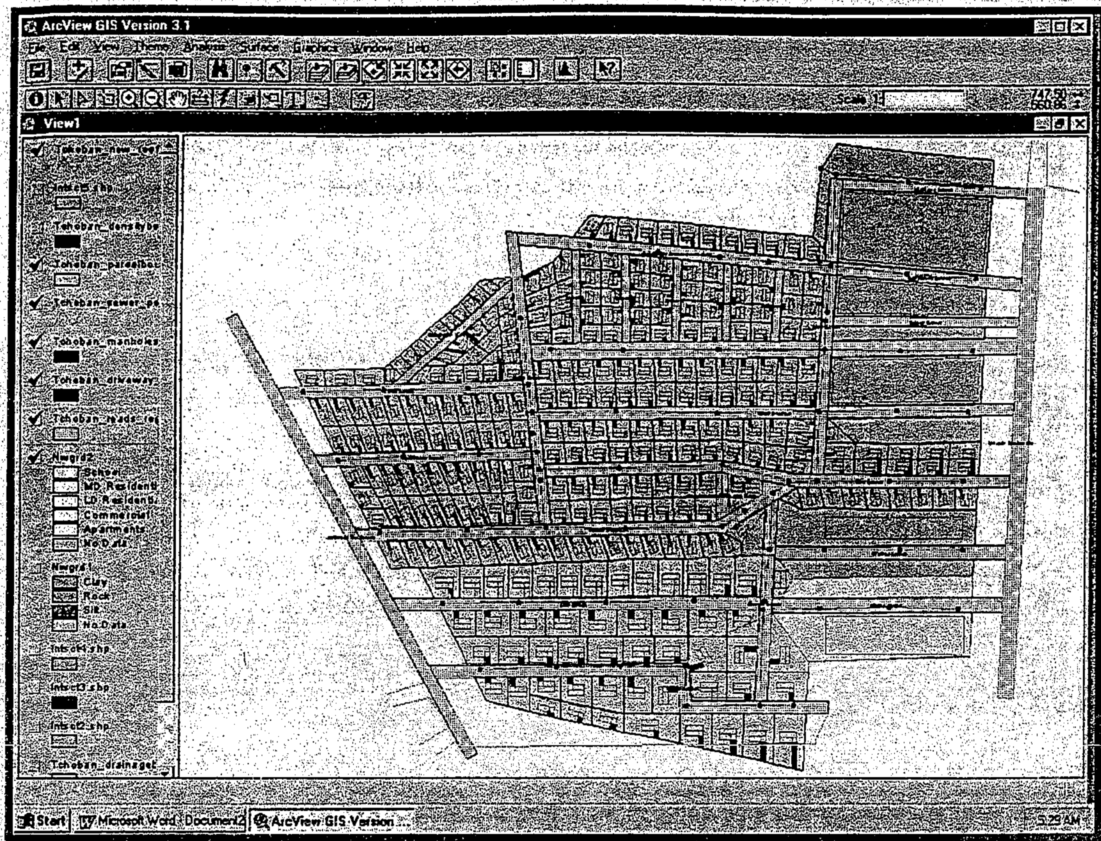


Figure 6-4. Study area GIS.

Associated with each graphic object, grouped according to type, is a relational database. Attributes associated with parcels are address and land area; and with streets are right-of-way width, length, land area, and street name. Soils and land use exist in separate tables, and this information is combined with the parcel and street databases by performing an intersection query on the two themes. The results of the query can also be output to an Excel spreadsheet by using ArcView's Avenue® script language and Microsoft's Dynamic Data Exchange® (DDE). This procedure was used to extract the relevant attribute information for parcels and streets.

### *6.4.1 Study area attributes*

The rights-of-way identified in Figures 6.4 and 6.5 were assigned widths based upon the following criteria. Most streets within the development have a 50 ft right-of-way, a minor arterial is given a 60 ft right-of-way, and a major arterial a 70 ft right-of-way. The profile for each right-of-way is given in Table 6-8.

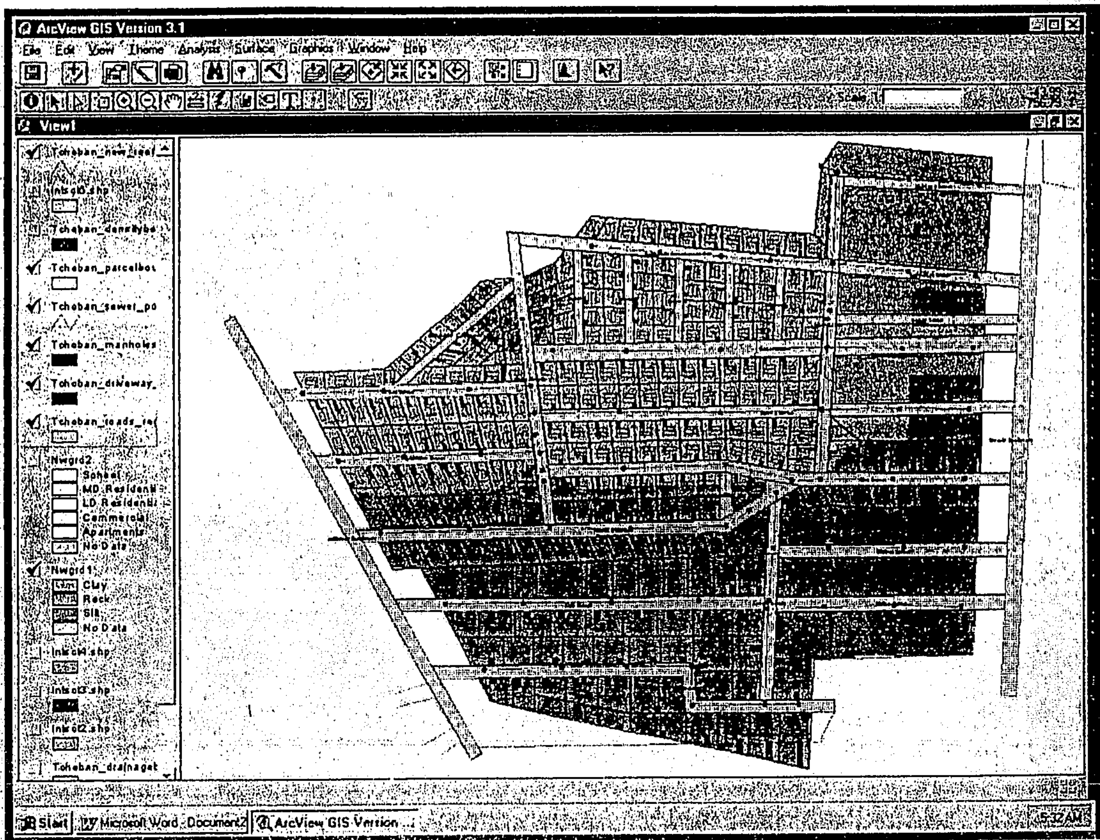



**Figure 6-5. Study area soils.**

**Table 6-8. Right-of-Way Characteristics***

| R/W (ft) | Length, (ft) | Curb (ft) | Parking (ft) | Landscaping strip (ft) | Sidewalk (ft) | Traffic Lanes (ft) |
|---|---|---|---|---|---|---|
| 50 | 28680 | 4 | 8 | 10 | 8 | 20 |
| 60 | 1124 | 4 | 16 | 10 | 8 | 22 |
| 70 | 2741 | 4 | 16 | 18 | 8 | 24 |

*** Some of the parameters are summed from both sides of the street.**

Lot characteristics for the two single lot residential land use classifications are tabulated in Table 6-9. Lots were aggregated in this manner for the optimization, but not for the detailed cost analysis.

**Table 6-9. Lot Characteristics for Residential Parcels**

| Land Use | # of Parcels | Roof Area ($ft^2$) | Patio ($ft^2$) | Driveway ($ft^2$) | Landscaping ($ft^2$) | Total Area ($ft^2$) |
|---|---|---|---|---|---|---|
| MD Residential (6–8 DU/AC) | 255 | 1,600 | 200 | 600 | 3,600 | 6,000 |
| LD Residential (2–5 DU/AC) | 51 | 2,000 | 400 | 800 | 9,800 | 13,000 |

For the apartments, commercial, and school land uses, an aggregated analysis was used. This is because these land uses exhibited multi-parcel characteristics, such as for parking uses. A summary of these characteristics is found in Table 6-10.

**Table 6-10. Aggregate Characteristics for Commercial, Apartments, and Schools**

| Land Use | Number of parcels | Stories | Parcel Area ($ft^2$) | Roof Area ($ft^2$) | Parking Area ($ft^2$) | Landscaping ($ft^2$) |
|---|---|---|---|---|---|---|
| Apartments | 2 | 2 | 162,680 | 46,927 | 75,083 | 40,670 |
| Commercial | 6 | 1 | 481,070 | 152,839 | 304,678 | 23,553 |
| School | 3 | 1 | 149,407 | 69,080 | 51,807 | 28,521 |

### *6.4.2 Unit costs*

Next, unit costs were developed for each development component. The results are presented below.

#### 6.4.2.1 Landscaping costs

Landscaping costs depend upon several factors, including opportunity costs, the cost of soil preparation including topsoil, sod, and soil conditioners, and an irrigation system. In order to determine the opportunity cost, a land valuation analysis must be done for each land use. Land valuation analysis for a medium density residential lot is presented in Table 6-11. The area of each component of the medium density lot is listed in column 2 of Table 6-11. The percentage of each component is calculated in column 3.

**Table 6-11. Land Valuation for Medium Density Lot**

| Component | Area ($ft^2$) | % of total | Cost (1/99 $/$ft^2$) | Construction Cost (1/99 $) | Total Land (1/99 $) | Unimproved Land (1/99 $) |
|---|---|---|---|---|---|---|
| Roof-house | 1,200 | 20.0 | 56.25 | 67,500 | 8,790 | 5,860 |
| Roof-garage | 400 | 6.7 | 34.00 | 13,600 | 2,930 | 1,953 |
| Driveway | 600 | 10.0 | 4.00 | 2,400 | 4,395 | 2,930 |
| Yard | 3,600 | 60.0 | 1.00 | 3,600 | 26,370 | 17,580 |
| Patio | 200 | 3.3 | 4.00 | 800 | 1,465 | 977 |
| Total | 6,000 | 100.0 | | 87,900 | 43,950 | 29,300 |

An estimate of the cost in $/$ft^2$ is found in column 4. Next, the construction cost is obtained by multiplying column 2 by column 4, and listing this in column 5. Next, the percentage in column 3 is multiplied by the total of column 5 to obtain an estimate of the land cost, in column 6. Column 7, the unimproved land cost, is obtained by multiplying the values in column 6 by 2/3. The value of the 3,600 $ft^2$ of land for the yard function is $26,370.

Next, opportunity costs must be calculated. This procedure is illustrated in Table 6-12. The value of $26,370 is annualized, using an interest rate of 6%, and an infinite term (as in equation 6.2), to obtain $1,582/yr. Then, this value is spread over 25 yrs at 6%, to obtain \$20,226. Dividing this value by 3,600 $ft^2$ gives \$5.62/$ft^2$. This value is used for all grass types because the underlying value of the land is assumed constant irrespective of the type of grass.

Landscaping costs were developed from RS Means (1996b), and updated to 1/99 \$, using the procedure shown in chapter 4 and are presented in Table 6-12 (for a medium density residential lot). The initial capital investment consists of the cost of soil preparation including sod, topsoil, and soil conditioners; and an irrigation system. For a good lawn, the present value of the initial landscaping investment is \$2.22/$ft^2$. Costs for lesser quality lawns drop to \$1.71/$ft^2$ and \$.95/$ft^2$ for fair and poor quality lawns. For the good lawn system, operation and maintenance costs add an additional \$2.45/$ft^2$ bringing the total to \$10.29/$ft^2$. An estimated 10% of this total cost is allocated to stormwater management. Similar estimates were made for fair and poor lawns. The resulting total costs per $ft^2$ vary from \$0.70 to \$1.03/$ft^2$. Better lawns have a lower CN and are thereby preferable from the viewpoint of being able to store more water. However, they also cost more. A linear programming model will be used to find the least costly mix.

Similar estimates were made for the land valuation of low density residential lots, commercial, apartments, and schools. A similar procedure was followed for these uses, except commercial, apartment, and school uses are aggregated as one lot. These valuations can be found in Table 6-13 for low density, Table 6-15, for commercial, Table 6-17 for apartments, and 6-19 for schools. Landscaping costs were determined the same way, and are found in Table 6-14 for low density residential, Table 6-16 for commercial, Table 6-18 for apartments, and Table 6-20 for schools.

Table 6-12. Cost Analysis of Landscaping for Medium Density Lot

| Item | Input Data | Good 1/99 $/ft² | Fair 1/99 $/ft² | Poor 1/99 $/ft² |
|---|---|---|---|---|
| **A. Initial Capital Investment** | | | | |
| 1. Soil preparation | | | | |
| Initial cost of sod | | 0.43 | 0.34 | 0.26 |
| Initial cost of topsoil, 6 in. | | 0.50 | 0.40 | 0.30 |
| Spreading topsoil, 6 in. | | 0.64 | 0.51 | 0.38 |
| Soil conditioners | | 0.03 | 0.02 | 0.01 |
| Sprinkler system | | 0.62 | 0.44 | 0.00 |
| | | 2.22 | 1.71 | 0.95 |
| 2. Opportunity Cost of Land | | | | |
| Land Investment Cost, $ | 26,370 | | | |
| Opportunity cost investment rate, % | 6 | | | |
| Annual cost, $/yr | 1,582 | | | |
| Interest rate/yr, % | 6 | | | |
| Present worth over 25 yr, $ | 20,226 | | | |
| Cost in $/ft² | | 5.62 | 5.62 | 5.62 |
| Total of initial capital investment | | 7.84 | 7.33 | 6.57 |
| **B. Operation & Maintenance Costs, $** | | | | |
| Lawn watering | | | | |
| in./yr | 20 | | | |
| % of permeable area that is irrigated | 80 | | | |
| Cost of water, $/1,000 gal | 1.50 | | | |
| Present worth factor | 12.78 | | | |
| Present worth, $/ft² | | 0.24 | 0.15 | 0.09 |
| Lawn maintenance | | | | |
| Weeks/yr | 26 | | | |
| $/week | 8.46 | | | |
| Maintenance area, ft² | 2880 | | | |
| Present worth, $/ft² | | 0.98 | 0.50 | 0.35 |
| Sprinkler system maintenance | | 0.25 | 0.15 | 0.00 |
| Total operation and maintenance costs, $ | | 1.46 | 0.80 | 0.44 |
| **C. Total Cost, $/ft²** | | 9.31 | 8.13 | 7.01 |
| **Portion attributable to stormwater** | | | | |
| Assumed % | 10 | | | |
| **D. Cost for Stormwater** | | 0.93 | 0.81 | 0.70 |

Table 6-13. Land Valuation for Low Density Lot

| Component | Area ($ft^2$) | % of total | Cost (1/99 $/$ft^2$) | Construction Cost (1/99 $) | Total Land Cost (1/99 $) | Unimproved Land Cost (1/99 $) |
|---|---|---|---|---|---|---|
| Roof-house | 1,600 | 12.3 | 56.25 | 90,000 | 7,274 | 4,849 |
| Roof-garage | 400 | 3.1 | 34.00 | 13,600 | 1,818 | 1,212 |
| Driveway | 800 | 6.2 | 4.00 | 3,200 | 3,637 | 2,425 |
| Yard | 9,800 | 75.4 | 1.00 | 9,800 | 44,552 | 29,702 |
| Patio | 400 | 3.1 | 4.00 | 1,600 | 1,818 | 1,212 |
| Total | 13,000 | 100.0 | | 118,200 | 59,100 | 39,400 |

Table 6-14. Cost Analysis of Landscaping for Low Density Lot

| Item | Input Data | Good $/$ft^2$ | Fair $/$ft^2$ | Poor $/$ft^2$ |
|---|---|---|---|---|
| **A. Initial Capital Investment** | | | | |
| 1. Soil preparation | | | | |
| Initial cost of sod | | 0.43 | 0.34 | 0.26 |
| Initial cost of topsoil, 6 in. | | 0.50 | 0.40 | 0.30 |
| Spreading topsoil, 6 in. | | 0.64 | 0.51 | 0.38 |
| Soil conditioners | | 0.03 | 0.02 | 0.01 |
| Sprinkler system | | 0.62 | 0.44 | 0.00 |
| | | 2.22 | 1.71 | 0.95 |
| 2. Opportunity Cost of Land | | | | |
| Land Investment Cost, $ | 44,552 | | | |
| Opportunity cost investment rate, % | 6 | | | |
| Annual cost, $/yr | 2,673 | | | |
| Interest rate/yr, % | 6 | | | |
| Present worth over 25 yr, $ | 34,172 | | | |
| Cost in $/$ft^2$ | | 3.49 | 3.49 | 3.49 |
| Total of initial capital investment | | 5.71 | 5.20 | 4.44 |
| **B. Operation & Maintenance Costs, $** | | | | |
| Lawn watering | | | | |
| in./yr | 20 | | | |
| % of permeable area that is irrigated | 80 | | | |
| Cost of water, $/1,000 gal | 1.50 | | | |
| Present worth factor | 12.78 | | | |
| Present worth, $/$ft^2$ | | 0.24 | 0.15 | 0.09 |
| Lawn maintenance | | | | |
| Weeks/yr | 26 | | | |
| $/week | 17.00 | | | |
| Maintenance area, $ft^2$ | 7840 | | | |
| Present worth, $/$ft^2$ | | 0.72 | 0.50 | 0.35 |
| Sprinkler system maintenance | | 0.25 | 0.15 | 0.00 |
| Total operation and maintenance costs, $ | | 1.21 | 0.80 | 0.44 |
| **C. Total Cost, $/$ft^2$** | | 6.92 | 6.00 | 4.88 |
| **Portion attributable to stormwater** | | | | |
| Assumed % | 10 | | | |
| **D. Cost for Stormwater** | | 0.69 | 0.60 | 0.49 |

Table 6-15. Land Valuation for Commercial Areas

| Component | Area ($ft^2$) | % of total | Cost (1/99 $/$ft^2$) | Construction Cost (1/99 $) | Total Land Cost (1/99 $) | Unimproved Land Cost (1/99 $) |
|---|---|---|---|---|---|---|
| Roof | 152,839 | 31.8 | 150.00 | 22,925,901 | 3,718,198 | 2,478,799 |
| Parking | 304,678 | 63.3 | 1.50 | 457,017 | 7,412,052 | 4,941,368 |
| Driveway | 0 | 0.0 | 1.50 | 0 | 0 | 0 |
| Yard | 23,553 | 4.9 | 1.00 | 23,553 | 572,985 | 381,990 |
| Patio | 0 | 0.0 | 4.00 | 0 | 0 | 0 |
| Total | 481,070 | 100.0 | | 23,406,471 | 11,703,236 | 7,802,157 |

Table 6-16. Cost Analysis of Landscaping for Commercial Areas

| Item | Input Data | Good 1/99 $/ft² | Fair 1/99 $/ft² | Poor 1/99 $/ft² |
|---|---|---|---|---|
| **A. Initial Capital Investment** | | | | |
| 1. Soil preparation | | | | |
| Initial cost of sod | | 0.43 | 0.34 | 0.26 |
| Initial cost of topsoil, 6 in. | | 0.50 | 0.40 | 0.30 |
| Spreading topsoil, 6 in. | | 0.64 | 0.51 | 0.38 |
| Soil conditioners | | 0.03 | 0.02 | 0.01 |
| Sprinkler system | | 0.62 | 0.44 | 0.00 |
| | | 2.22 | 1.71 | 0.95 |
| 2. Opportunity Cost of Land | | | | |
| Land Investment Cost, $ | 572,985 | | | |
| Opportunity cost investment rate | 6 | | | |
| Annual cost, $/yr | 34,379 | | | |
| Interest rate/yr, % | 6 | | | |
| Present worth over 25 yr, $ | 439,481 | | | |
| Cost in $/ft² | | 18.66 | 18.66 | 18.66 |
| Total of initial capital investment | | 20.88 | 20.37 | 19.61 |
| **B. Operation & Maintenance Costs, $** | | | | |
| Lawn watering | | | | |
| In./yr | 20 | | | |
| % of permeable area that is irrigated | 100 | | | |
| Cost of water, $/1,000 gal | 1.50 | | | |
| Present worth factor | 12.78 | | | |
| Present worth, $/ft² | | 0.24 | 0.15 | 0.09 |
| Lawn maintenance | | | | |
| Weeks/yr | 26 | | | |
| $/week | 33.26 | | | |
| Maintenance area, ft² | 23553 | | | |
| Present worth, $/ft² | | 0.47 | 0.50 | 0.35 |
| Sprinkler system maintenance | | 0.25 | 0.15 | 0.00 |
| Total operation and maintenance costs, $ | | 0.96 | 0.80 | 0.44 |
| **C. Total Cost, $/ft²** | | 21.84 | 21.17 | 20.05 |
| **Portion attributable to stormwater** | | | | |
| Assumed % | 10 | | | |
| **D. Cost for Stormwater** | | 2.18 | 2.12 | 2.01 |

Table 6-17. Land Valuation for Apartments

| Component | Area ($ft^2$) | % of total | Cost (1/99 $/$ft^2$) | Construction Cost (1/99 $) | Total Land Cost (1/99 $) | Unimproved Land Cost (1/99$) |
|---|---|---|---|---|---|---|
| Roof | 46,927 | 28.8 | 84.38 | 3,959,466 | 593,187 | 395,458 |
| Parking | 75,083 | 46.2 | 1.50 | 112,625 | 949,100 | 632,733 |
| Driveway | 0 | 0.0 | 1.50 | 0 | 0 | 0 |
| Yard | 40,670 | 25.0 | 1.00 | 40,670 | 514,093 | 342,729 |
| Patio | 0 | 0.0 | 4.00 | 0 | 0 | 0 |
| Total | 162,680 | 100.0 | | 4,112,760 | 2,056,380 | 1,370,920 |

Table 6-18. Cost Analysis of Landscaping for Apartments

| Item | Input Data | Good 1/99 $/$ft^2$ | Fair 1/99 $/$ft^2$ | Poor 1/99 $/$ft^2$ |
|---|---|---|---|---|
| **A. Initial Capital Investment** | | | | |
| 1. Soil preparation | | | | |
| Initial cost of sod | | 0.43 | 0.34 | 0.26 |
| Initial cost of topsoil, 6 in. | | 0.50 | 0.40 | 0.30 |
| Spreading topsoil, 6 in. | | 0.64 | 0.51 | 0.38 |
| Soil conditioners | | 0.03 | 0.02 | 0.01 |
| Sprinkler system | | 0.62 | 0.44 | 0.00 |
| | | 2.22 | 1 | 0.95 |
| 2. Opportunity Cost of Land | | | | |
| Land Investment Cost | 514,093 | | | |
| Opportunity cost investment rate | 6 | | | |
| Annual cost, $/yr | 30,846 | | | |
| Interest rate/yr, % | 6 | | | |
| Present worth over 25 yr, $ | 394,310 | | | |
| Cost in $/$ft^2$ | | 9.70 | 9.70 | 9.70 |
| Total of initial capital investment | | 11.92 | 11.41 | 10.65 |
| **B. Operation & Maintenance Costs, $** | | | | |
| Lawn watering | | | | |
| In./yr | 20 | | | |
| % of permeable area that is irrigated | 80 | | | |
| Cost of water, $/1,000 gal | 1.50 | | | |
| Present worth factor | 12.78 | | | |
| Present worth, $/$ft^2$ | | 0.24 | 0.15 | 0.09 |
| Lawn maintenance | | | | |
| Weeks/yr | 26 | | | |
| $/week | 44.04 | | | |
| Maintenance area, $ft^2$ | 32536 | | | |
| Present worth, $/$ft^2$ | | 0.45 | 0.50 | 0.35 |
| Sprinkler system maintenance | | 0.25 | 0.15 | 0.00 |
| Total operation and maintenance costs, $ | | 0.94 | 0.80 | 0.44 |
| **C. Total Cost, $/$ft^2$** | | 12.86 | 12.21 | 11.09 |
| **Portion attributable to stormwater** | | | | |
| Assumed % | 10 | | | |
| **D. Cost for Stormwater** | | 1.29 | 1.22 | 1.11 |

Table 6-19. Land Valuation for Schools

| Component | Area ($ft^2$) | % of Total | Cost (1/99 $/$ft^2$) | Construction Cost (1/99 $) | Total Land Cost (1/99 $) | Unimproved Land Cost (1/99 $) |
|---|---|---|---|---|---|---|
| Roof | 46,927 | 28.8 | 84.38 | 8,635,000 | 2,020,799 | 1,347,199 |
| Parking | 75,083 | 46.2 | 1.50 | 77,709 | 1,515,482 | 1,010,322 |
| Driveway | 0 | 0.0 | 1.50 | 0 | 0 | 0 |
| Yard | 40,670 | 25.0 | 1.00 | 28,521 | 834,334 | 556,222 |
| Patio | 0 | 0.0 | 4.00 | 0 | 0 | 0 |
| Total | 162,680 | 100.0 | | 8,741,230 | 4,370,615 | 2,913,743 |

Table 6-20. Cost Analysis of Landscaping for Schools

| Item | Input Data | Good 1/99 $/ft² | Fair 1/99 $/ft² | Poor 1/99 $/ft² |
|---|---|---|---|---|
| **A. Initial Capital Investment** | | | | |
| 1. Soil preparation | | | | |
| Initial cost of sod | | 0.43 | 0.34 | 0.26 |
| Initial cost of topsoil, 6 in. | | 0.50 | 0.40 | 0.30 |
| Spreading topsoil, 6 in. | | 0.64 | 0.51 | 0.38 |
| Soil conditioners | | 0.03 | 0.02 | 0.01 |
| Sprinkler system | | 0.62 | 0.44 | 0.00 |
| | | 2.22 | 1.71 | 0.95 |
| 2. Opportunity Cost of Land | | | | |
| Land Investment Cost, $ | 834,334 | | | |
| Opportunity cost investment rate, % | 6 | | | |
| Annual cost, $/yr | 50,060 | | | |
| Interest rate/yr, % | 6 | | | |
| Present worth over 25 yr, $ | 639,935 | | | |
| Cost in $/ft² | | 22.44 | 22.44 | 22.44 |
| Total of initial capital investment | | 24.66 | 24.15 | 23.39 |
| **B. Operation & Maintenance Costs, $** | | | | |
| Lawn watering | | | | |
| In. per year | 20 | | | |
| % of permeable area that is irrigated | 80 | | | |
| Cost of water, $/1,000 gal | 1.50 | | | |
| Present worth factor | 12.78 | | | |
| Present worth, $/ft² | | 0.24 | 0.15 | 0.09 |
| Lawn maintenance | | | | |
| Weeks/yr | 26 | | | |
| $/week | 32.38 | | | |
| Maintenance area, ft² | 22817 | | | |
| Present worth, $/ft² | | 0.47 | 0.50 | 0.35 |
| Sprinkler system maintenance | | 0.25 | 0.15 | 0.00 |
| Total operation and maintenance costs, $ | | 0.96 | 0.80 | 0.44 |
| **C. Total Cost, $/ft²** | | 25.62 | 24.95 | 23.83 |
| **Portion attributable to stormwater** | | | | |
| Assumed % | 10 | | | |
| **D. Cost for Stormwater** | | 2.56 | 2.49 | 2.38 |

6.4.2.2 Right-of-way costs

Based upon the paving costs shown in Table 3-7 (explained in equations 3.4 to 3.8 and the profile selected from Table 6-8), costs were assigned to each right-of-way. These costs are presented as \$/linear foot, assuming the widths from Table 6-8, and are presented in Table 6-21.

**Table 6-21. Costs of Pavement, Curb and Gutter, and Sidewalks***

| Right-of-Way | Curb (1/99 \$) | Pavement (1/99 \$) | Sidewalks (1/99 \$) |
|---|---|---|---|
| 50 | 13.89 | 33.63 | 2.40 |
| 60 | 13.89 | 45.64 | 2.40 |
| 70 | 13.89 | 48.04 | 2.40 |

*** Curbs are assumed to be both sides of the street with 2 ft in width**

Unit costs are \$3.47/ft$^2$ for curbs, \$1.20/ft$^2$ for pavement, and \$.30/ft$^2$ for sidewalks. Since the area of each paved surface is known, these ft$^2$ estimates can be multiplied by this area to obtain the total cost. Alternatively, the length (within each right-of-way type) may be multiplied by the unit factors found in Table 6-21.

The total right-of-way costs are not just a function of pavement costs. There is an opportunity cost to devoting land for right-of-way instead of for development. Several different methods can be used for determining the value of the right-of-way; the one selected here is that of using the lowest valued use, which is the opportunity cost for undeveloped land for low density residential use, or \$3.49/ft$^2$. This method is consistent with marginal cost analysis. Several street profiles were analyzed, and are shown in Table 6-22. Street 1 is a standard street with curb and gutter. Street 2 is a street with porous pavement and curb and gutter. Street 3 is a standard pavement street with swales. Street 4 is a street with porous pavement and swales. Because the right-of-way must remain constant, the travel lane was reduced in the case of streets using swales. These costs are added to the opportunity cost and apportioned to stormwater as shown in Table 6-22.

Table 6-22. Cost Analysis for 50 ft Right-of-Way

| Item | Input Data | Street 1 (1/99 $/ft$^2$) | Street 2 (1/99 $/ft$^2$) | Street 3 (1/99 $/ft$^2$) | Street 4 (1/99 $/ft$^2$) |
|---|---|---|---|---|---|
| **A. Initial Capital Investment** | | | | | |
| Opportunity Cost: Low Density Residential | | 3.49 | 3.49 | 3.49 | 3.49 |
| **B. Pavement Costs** | | | | | |
| width of street, ft | 32 | | | | |
| width of swales, ft | | | | 12 | 12 |
| width of pavement, ft | | 28 | 28 | 20 | 20 |
| Swales, $/ft$^2$ | 3.00 | | | 36.00 | 36.00 |
| curb and gutter, $/ft | | 13.89 | 13.89 | | |
| pavement, $/ft | | 33.63 | 42.04 | 24.02 | 30.03 |
| total, $/ft | | 47.52 | 55.93 | 60.02 | 66.03 |
| total of B, $/ft$^2$ | | 1.49 | 1.75 | 1.88 | 2.06 |
| **C. Total, $/ft$^2$** | | 4.97 | 5.23 | 5.36 | 5.55 |
| **Portion attributable to stormwater** | | | | | |
| Assumed, % | 5 | | | | |
| **D. Cost for Stormwater** | | 0.25 | 0.26 | 0.27 | 0.28 |

Similar analysis can be performed for 60 and 70 ft right-of-way streets. These results are presented in Tables 6.23 and 6.24.

Table 6-23. Cost Analysis for 60 ft Right-of-Way

| Item | Input Data | Street 1 (1/99 $/ft$^2$) | Street 2 (1/99 $/ft$^2$) | Street 3 (1/99 $/ft$^2$) | Street 4 (1/99 $/ft$^2$) |
|---|---|---|---|---|---|
| **A. Initial Capital Investment** | | | | | |
| Opportunity Cost: Low Density Residential | | 3.49 | 3.49 | 3.49 | 3.49 |
| **B. Pavement Costs** | | | | | |
| width of street, ft | 42 | | | | |
| width of swales, ft | | | | 12 | 12 |
| width of pavement, ft | | 38 | 38 | 38 | 38 |
| swales, $/ft$^2$ | 3.00 | | | 36 | 36 |
| curb and gutter, $/ft | | 13.89 | 13.89 | | |
| pavement, $/ft | | 45.64 | 57.05 | 45.64 | 57.05 |
| total, $/ft | | 59.54 | 70.95 | 81.64 | 93.05 |
| total, $/ft$^2$ | | 1.42 | 1.69 | 1.94 | 2.22 |
| **C. Total, $/ft$^2$** | | 4.90 | 5.18 | 5.43 | 5.70 |
| **Portion attributable to stormwater** | | | | | |
| Assumed, % | 5 | | | | |
| **D. Cost for Stormwater** | | 0.25 | 0.26 | 0.27 | 0.29 |

Proceeding from left to right in Tables 6.22 through 6.24, the streets have increasingly better infiltration characteristics. This is reflected in the curve numbers for the street, however, the street becomes more expensive. A linear program model can be used to determine the least costly mix.

**Table 6-24. Cost Analysis for 70 ft Right-of-Way**

| Item | Input Data | Street 1 (1/99 $/ft²) | Street 2 (1/99 $/ft²) | Street 3 (1/99 $/ft²) | Street 4 (1/99 $/ft²) |
|---|---|---|---|---|---|
| **A. Initial Capital Investment** | | | | | |
| Opportunity Cost: Low Density Residential | | 3.49 | 3.49 | 3.49 | 3.49 |
| **B. Pavement Costs** | | | | | |
| width of street, ft | 44 | | | | |
| width of swales, ft | | | | 12 | 12 |
| width of pavement, ft | | 40 | 40 | 40 | 40 |
| swales, $/ft² | 3.00 | | | 36.00 | 36.00 |
| curb and gutter, $/ft | | 13.89 | 13.89 | | |
| pavement, $/ft | | 48.04 | 60.05 | 48.04 | 60.05 |
| Total, $/ft | | 61.94 | 73.95 | 84.04 | 96.05 |
| Total, $/ft² | | 1.41 | 1.68 | 1.91 | 2.18 |
| **C. Total, $/ft²** | | 4.89 | 5.17 | 5.40 | 5.67 |
| **Portion attributable to stormwater** | | | | | |
| Assumed, % | 5 | | | | |
| **D. Cost for Stormwater** | | 0.24 | 0.26 | 0.27 | 0.28 |

6.4.2.3 Costs for other land functions

The costs of parking, sidewalks and patios, and driveways were determined using a similar procedure. Parking lots were evaluated in the following forms: standard pavement, and three types of porous pavement of gradually increasing permeability. The cost analysis for parking is shown in Table 6-25. As the permeability of the parking area increases, it is given a lower curve number, but the cost rises as well. This can be investigated using a linear program model. A ratio of 5% was used to apportion the costs to stormwater.

**Table 6-25. Cost Analysis for Parking**

| Item | Input Data | Parking 1 (1/99 $/ft²) | Parking 2 (1/99 $/ft²) | Parking 3 (1/99 $/ft²) | Parking 4 (1/99 $/ft²) |
|---|---|---|---|---|---|
| **A. Initial Capital Investment** | | | | | |
| Opportunity Cost: Low Density Residential | | 3.49 | 3.49 | 3.49 | 3.49 |
| **B. Pavement Costs** | | | | | |
| paving costs, $/ft² | 1.20 | 1.20 | 1.50 | 1.80 | 2.10 |
| **C. Total, $/ft²** | | 4.69 | 4.99 | 5.29 | 5.59 |
| **Portion attributable to stormwater** | | | | | |
| Assumed % | 5 | | | | |
| **D. Cost for Stormwater** | | 0.23 | 0.25 | 0.26 | 0.28 |

Two types of sidewalks were evaluated, standard and porous, and two types of patios, standard and porous. This analysis is shown in Table 6-26. Again, with the second sidewalk (or patio), the curve number decreases as the infiltration performance increases, however the cost also increases, albeit very slightly. A ratio of 5% was apportioned to stormwater costs.

**Table 6-26. Cost Analysis for Sidewalks and Patios**

| Item | Input Data | Sidewalk1/ Patio1 (1/99 $/ft$^2$) | Sidewalk2/ Patio2 (1/99 $/ft$^2$) |
|---|---|---|---|
| **A. Initial Capital Investment** | | | |
| Opportunity Cost: Low Density Residential | | 3.49 | 3.49 |
| **B. Pavement Costs** | | | |
| Sidewalk costs, $/ft$^2$ | 0.30 | 0.30 | 0.38 |
| **C. Total, $/ft$^2$** | | 3.79 | 3.86 |
| **Portion attributable to stormwater** | | | |
| Assumed, % | 5 | | |
| **D. Cost for Stormwater** | | 0.19 | 0.19 |

Two types of driveways were evaluated, standard and porous, and this analysis is shown in Table 6-27. Again, with the second driveway, as the permeability increases, the curve number decreases, but the cost increases. A ratio of 5% was apportioned to stormwater costs.

**Table 6-27. Cost Analysis for Driveways**

| Item | Input Data | Driveway 1 (1/99 $/ft$^2$) | Driveway 2 (1/99 $/ft$^2$) |
|---|---|---|---|
| **A. Initial Capital Investment** | | | |
| Opportunity Cost: Low Density Residential | | 3.49 | 3.49 |
| **B. Pavement Costs** | | | |
| Paving costs, $/ft$^2$ | 1.20 | 1.20 | 1.50 |
| **C. Total, $/ft$^2$** | | 4.69 | 4.99 |
| **Portion attributable to stormwater** | | | |
| Assumed, % | 5 | | |
| **D. Cost for Stormwater** | | 0.23 | 0.25 |

### *6.4.3 Summary of costs for each parcel*

Based upon the landscaping costs shown in Tables 6-12, 6-14, 6-16, 6-18, and 6-20, the costs for parking in Table 6-25, the cost for sidewalks in Table 6-26, and the cost for driveways in Table 6-27, costs were assigned to each parcel. These costs are presented in Table 6-28. These costs are based upon the rooflines calculated directly from the figures or listed in Tables 6-9 (for single family residential lots) and the total parcel area. The total landscaping costs for the developed area is $14.5 million. The parking areas total $2 million, and the driveways total $969,000. These costs include opportunity costs.

Table 6-28. Parcel Development Costs

| Address | Street | Soil | Land Use | Area ($ft^2$) | Roof ($ft^2$) | Parking ($ft^2$) | Drive-ways ($ft^2$) | Patios ($ft^2$) | Impervious ($ft^2$) | Pervious ($ft^2$) | Landscaping (1/99 $) | Parking (1/99 $) | Driveway (1/99 $) | Total (1/99 $) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 100 | Alpine Street | Silt | Apartments | 50320 | 0 | 37740 | 0 | 0 | 37740 | 12580 | 159,000 | 177,000 | 0 | 336,000 |
| 101 | Alpine Street | Silt | Apartments | 112360 | 46927 | 37343 | 0 | 0 | 84270 | 28090 | 354,000 | 176,000 | 0 | 530,000 |
| 200 | Cedar Street | Clay | Commercial | 25957 | 0 | 24659 | 0 | 0 | 24659 | 1298 | 29,000 | 116,000 | 0 | 145,000 |
| 200 | Ashmount Street | Rock | Commercial | 154915 | 57707 | 89462 | 0 | 0 | 147169 | 7746 | 168,000 | 420,000 | 0 | 588,000 |
| 201 | Ashmount Street | Rock | Commercial | 72968 | 0 | 69319 | 0 | 0 | 69319 | 3648 | 79,000 | 325,000 | 0 | 404,000 |
| 100 | Highland Street | Rock | Commercial | 80450 | 0 | 76427 | 0 | 0 | 76427 | 4022 | 87,000 | 359,000 | 0 | 446,000 |
| 200 | Birch Avenue | Silt | Commercial | 100139 | 95132 | 0 | 0 | 0 | 95132 | 5007 | 109,000 | 0 | 0 | 109,000 |
| 201 | Birch Avenue | Silt | Commercial | 46642 | 0 | 44810 | 0 | 0 | 44810 | 1832 | 40,000 | 211,000 | 0 | 251,000 |
| 105 | Center Street | Silt | LD Residential | 14235 | 2000 | | 800 | 400 | 3200 | 11035 | 77,000 | 0 | 4,000 | 81,000 |
| 110 | Center Street | Silt | LD Residential | 18488 | 2000 | | 800 | 400 | 3200 | 15288 | 106,000 | 0 | 4,000 | 110,000 |
| 120 | Center Street | Silt | LD Residential | 6844 | 2000 | | 800 | 400 | 3200 | 3644 | 26,000 | 0 | 4,000 | 30,000 |
| 100 | Maple Street | Silt | LD Residential | 15082 | 2000 | | 800 | 400 | 3200 | 11882 | 83,000 | 0 | 4,000 | 87,000 |
| 101 | Maple Street | Silt | LD Residential | 9927 | 2000 | | 800 | 400 | 3200 | 6727 | 47,000 | 0 | 4,000 | 51,000 |
| 102 | Maple Street | Silt | LD Residential | 11751 | 2000 | | 800 | 400 | 3200 | 8551 | 60,000 | 0 | 4,000 | 64,000 |
| 103 | Maple Street | Silt | LD Residential | 9742 | 2000 | | 800 | 400 | 3200 | 6542 | 46,000 | 0 | 4,000 | 50,000 |
| 104 | Maple Street | Silt | LD Residential | 11025 | 2000 | | 800 | 400 | 3200 | 7825 | 55,000 | 0 | 4,000 | 59,000 |
| 105 | Maple Street | Silt | LD Residential | 8744 | 2000 | | 800 | 400 | 3200 | 5544 | 39,000 | 0 | 4,000 | 43,000 |
| 106 | Maple Street | Silt | LD Residential | 11441 | 2000 | | 800 | 400 | 3200 | 8241 | 58,000 | 0 | 4,000 | 62,000 |
| 107 | Maple Street | Silt | LD Residential | 7667 | 2000 | | 800 | 400 | 3200 | 4467 | 31,000 | 0 | 4,000 | 35,000 |
| 108 | Maple Street | Silt | LD Residential | 12942 | 2000 | | 800 | 400 | 3200 | 9742 | 68,000 | 0 | 4,000 | 72,000 |
| 109 | Maple Street | Silt | LD Residential | 11518 | 2000 | | 800 | 400 | 3200 | 8318 | 58,000 | 0 | 4,000 | 62,000 |
| 110 | Maple Street | Silt | LD Residential | 11728 | 2000 | | 800 | 400 | 3200 | 8528 | 60,000 | 0 | 4,000 | 64,000 |
| 111 | Maple Street | Silt | LD Residential | 7707 | 2000 | | 800 | 400 | 3200 | 4507 | 32,000 | 0 | 4,000 | 36,000 |
| 112 | Maple Street | Silt | LD Residential | 12053 | 2000 | | 800 | 400 | 3200 | 8853 | 62,000 | 0 | 4,000 | 66,000 |
| 113 | Maple Street | Silt | LD Residential | 14291 | 2000 | | 800 | 400 | 3200 | 11091 | 77,000 | 0 | 4,000 | 81,000 |
| 114 | Maple Street | Silt | LD Residential | 17653 | 2000 | | 800 | 400 | 3200 | 14453 | 101,000 | 0 | 4,000 | 105,000 |
| 115 | Maple Street | Silt | LD Residential | 8015 | 2000 | | 800 | 400 | 3200 | 4815 | 34,000 | 0 | 4,000 | 38,000 |
| 116 | Maple Street | Silt | LD Residential | 13857 | 2000 | | 800 | 400 | 3200 | 10657 | 74,000 | 0 | 4,000 | 78,000 |
| 117 | Maple Street | Silt | LD Residential | 13778 | 2000 | | 800 | 400 | 3200 | 10578 | 74,000 | 0 | 4,000 | 78,000 |
| 118 | Maple Street | Silt | LD Residential | 11207 | 2000 | | 800 | 400 | 3200 | 8007 | 56,000 | 0 | 4,000 | 60,000 |
| 119 | Maple Street | Silt | LD Residential | 18674 | 2000 | | 800 | 400 | 3200 | 15474 | 108,000 | 0 | 4,000 | 112,000 |
| 120 | Maple Street | Silt | LD Residential | 15565 | 2000 | | 800 | 400 | 3200 | 12365 | 86,000 | 0 | 4,000 | 90,000 |
| 121 | Maple Street | Silt | LD Residential | 13029 | 2000 | | 800 | 400 | 3200 | 9829 | 69,000 | 0 | 4,000 | 73,000 |
| 123 | Maple Street | Silt | LD Residential | 14017 | 2000 | | 800 | 400 | 3200 | 10817 | 75,000 | 0 | 4,000 | 79,000 |
| 125 | Maple Street | Silt | LD Residential | 16758 | 2000 | | 800 | 400 | 3200 | 13558 | 94,000 | 0 | 4,000 | 98,000 |
| 127 | Maple Street | Silt | LD Residential | 19500 | 2000 | | 800 | 400 | 3200 | 16300 | 113,000 | 0 | 4,000 | 117,000 |
| 129 | Maple Street | Silt | LD Residential | 22449 | 2000 | | 800 | 400 | 3200 | 19249 | 134,000 | 0 | 4,000 | 138,000 |
| 100 | Oak Street | Silt | LD Residential | 14049 | 2000 | | 800 | 400 | 3200 | 10849 | 76,000 | 0 | 4,000 | 80,000 |
| 101 | Oak Street | Silt | LD Residential | 10172 | 2000 | | 800 | 400 | 3200 | 6972 | 49,000 | 0 | 4,000 | 53,000 |
| 102 | Oak Street | Silt | LD Residential | 11049 | 2000 | | 800 | 400 | 3200 | 7849 | 55,000 | 0 | 4,000 | 59,000 |
| 106 | Oak Street | Silt | LD Residential | 11131 | 2000 | | 800 | 400 | 3200 | 7931 | 55,000 | 0 | 4,000 | 59,000 |
| 108 | Oak Street | Silt | LD Residential | 11239 | 2000 | | 800 | 400 | 3200 | 8039 | 56,000 | 0 | 4,000 | 60,000 |
| 110 | Oak Street | Silt | LD Residential | 11681 | 2000 | | 800 | 400 | 3200 | 8481 | 59,000 | 0 | 4,000 | 63,000 |
| 120 | Oak Street | Silt | LD Residential | 11993 | 2000 | | 800 | 400 | 3200 | 8793 | 61,000 | 0 | 4,000 | 65,000 |
| 121 | Oak Street | Silt | LD Residential | 12611 | 2000 | | 800 | 400 | 3200 | 9411 | 66,000 | 0 | 4,000 | 70,000 |

| Add-ress | Street | Soil | Land Use | Area ($ft^2$) | Roof ($ft^2$) | Parking ($ft^2$) | Drive-ways ($ft^2$) | Patios ($ft^2$) | Impervious ($ft^2$) | Pervious ($ft^2$) | Landscaping (1/99 $) | Parking (1/99 $) | Driveway (1/99 $) | Total (1/99 $) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 130 | Oak Street | Silt | LD Residential | 12127 | 2000 | | 800 | 400 | 3200 | 8927 | 62,000 | 0 | 4,000 | 66,000 |
| 131 | Oak Street | Silt | LD Residential | 12680 | 2000 | | 800 | 400 | 3200 | 9480 | 66,000 | 0 | 4,000 | 70,000 |
| 140 | Oak Street | Silt | LD Residential | 12646 | 2000 | | 800 | 400 | 3200 | 9446 | 66,000 | 0 | 4,000 | 70,000 |
| 141 | Oak Street | Silt | LD Residential | 12749 | 2000 | | 800 | 400 | 3200 | 9549 | 67,000 | 0 | 4,000 | 71,000 |
| 150 | Oak Street | Silt | LD Residential | 13048 | 2000 | | 800 | 400 | 3200 | 9848 | 69,000 | 0 | 4,000 | 73,000 |
| 151 | Oak Street | Silt | LD Residential | 12818 | 2000 | | 800 | 400 | 3200 | 9618 | 67,000 | 0 | 4,000 | 71,000 |
| 160 | Oak Street | Silt | LD Residential | 12950 | 2000 | | 800 | 400 | 3200 | 9750 | 68,000 | 0 | 4,000 | 72,000 |
| 161 | Oak Street | Silt | LD Residential | 12886 | 2000 | | 800 | 400 | 3200 | 9686 | 68,000 | 0 | 4,000 | 72,000 |
| 170 | Oak Street | Silt | LD Residential | 13016 | 2000 | | 800 | 400 | 3200 | 9816 | 68,000 | 0 | 4,000 | 72,000 |
| 171 | Oak Street | Silt | LD Residential | 12955 | 2000 | | 800 | 400 | 3200 | 9755 | 68,000 | 0 | 4,000 | 72,000 |
| 180 | Oak Street | Silt | LD Residential | 13412 | 2000 | | 800 | 400 | 3200 | 10212 | 71,000 | 0 | 4,000 | 75,000 |
| 181 | Oak Street | Silt | LD Residential | 13618 | 2000 | | 800 | 400 | 3200 | 10418 | 73,000 | 0 | 4,000 | 77,000 |
| 190 | Oak Street | Silt | LD Residential | 14363 | 2000 | | 800 | 400 | 3200 | 11163 | 78,000 | 0 | 4,000 | 82,000 |
| 191 | Oak Street | Silt | LD Residential | 11552 | 2000 | | 800 | 400 | 3200 | 8352 | 58,000 | 0 | 4,000 | 62,000 |
| 151 | Acorn Street | Clay | MD Residential | 6019 | 1600 | | 600 | 200 | 2400 | 3619 | 38,000 | 0 | 3,000 | 41,000 |
| 160 | Acorn Street | Clay | MD Residential | 5286 | 1600 | | 600 | 200 | 2400 | 2886 | 30,000 | 0 | 3,000 | 33,000 |
| 161 | Acorn Street | Clay | MD Residential | 3926 | 1600 | | 600 | 200 | 2400 | 1526 | 16,000 | 0 | 3,000 | 19,000 |
| 165 | Acorn Street | Clay | MD Residential | 3853 | 1600 | | 600 | 200 | 2400 | 1453 | 15,000 | 0 | 3,000 | 18,000 |
| 170 | Acorn Street | Clay | MD Residential | 5543 | 1600 | | 600 | 200 | 2400 | 3143 | 33,000 | 0 | 3,000 | 36,000 |
| 171 | Acorn Street | Clay | MD Residential | 3926 | 1600 | | 600 | 200 | 2400 | 1526 | 16,000 | 0 | 3,000 | 19,000 |
| 176 | Acorn Street | Clay | MD Residential | 5800 | 1600 | | 600 | 200 | 2400 | 3400 | 35,000 | 0 | 3,000 | 38,000 |
| 179 | Acorn Street | Clay | MD Residential | 3926 | 1600 | | 600 | 200 | 2400 | 1526 | 16,000 | 0 | 3,000 | 19,000 |
| 180 | Acorn Street | Clay | MD Residential | 4788 | 1600 | | 600 | 200 | 2400 | 2388 | 25,000 | 0 | 3,000 | 28,000 |
| 181 | Acorn Street | Clay | MD Residential | 3926 | 1600 | | 600 | 200 | 2400 | 1526 | 16,000 | 0 | 3,000 | 19,000 |
| 182 | Acorn Street | Clay | MD Residential | 4783 | 1600 | | 600 | 200 | 2400 | 2383 | 25,000 | 0 | 3,000 | 28,000 |
| 100 | Ash Street | Clay | MD Residential | 5750 | 1600 | | 600 | 200 | 2400 | 3350 | 35,000 | 0 | 3,000 | 38,000 |
| 101 | Ash Street | Clay | MD Residential | 6785 | 1600 | | 600 | 200 | 2400 | 4385 | 46,000 | 0 | 3,000 | 49,000 |
| 110 | Ash Street | Clay | MD Residential | 6600 | 1600 | | 600 | 200 | 2400 | 4200 | 44,000 | 0 | 3,000 | 47,000 |
| 111 | Ash Street | Clay | MD Residential | 6765 | 1600 | | 600 | 200 | 2400 | 4365 | 45,000 | 0 | 3,000 | 48,000 |
| 120 | Ash Street | Clay | MD Residential | 6620 | 1600 | | 600 | 200 | 2400 | 4220 | 44,000 | 0 | 3,000 | 47,000 |
| 121 | Ash Street | Clay | MD Residential | 6744 | 1600 | | 600 | 200 | 2400 | 4344 | 45,000 | 0 | 3,000 | 48,000 |
| 131 | Ash Street | Clay | MD Residential | 6724 | 1600 | | 600 | 200 | 2400 | 4324 | 45,000 | 0 | 3,000 | 48,000 |
| 135 | Ash Street | Clay | MD Residential | 6703 | 1600 | | 600 | 200 | 2400 | 4303 | 45,000 | 0 | 3,000 | 48,000 |
| 139 | Ash Street | Clay | MD Residential | 6683 | 1600 | | 600 | 200 | 2400 | 4283 | 45,000 | 0 | 3,000 | 48,000 |
| 141 | Ash Street | Clay | MD Residential | 6662 | 1600 | | 600 | 200 | 2400 | 4262 | 44,000 | 0 | 3,000 | 47,000 |
| 150 | Ash Street | Clay | MD Residential | 3919 | 1600 | | 600 | 200 | 2400 | 1519 | 16,000 | 0 | 3,000 | 19,000 |
| 151 | Ash Street | Clay | MD Residential | 6642 | 1600 | | 600 | 200 | 2400 | 4242 | 44,000 | 0 | 3,000 | 47,000 |
| 160 | Ash Street | Clay | MD Residential | 4481 | 1600 | | 600 | 200 | 2400 | 2081 | 22,000 | 0 | 3,000 | 25,000 |
| 161 | Ash Street | Clay | MD Residential | 6621 | 1600 | | 600 | 200 | 2400 | 4221 | 44,000 | 0 | 3,000 | 47,000 |
| 170 | Ash Street | Clay | MD Residential | 4763 | 1600 | | 600 | 200 | 2400 | 2363 | 25,000 | 0 | 3,000 | 28,000 |
| 171 | Ash Street | Clay | MD Residential | 6601 | 1600 | | 600 | 200 | 2400 | 4201 | 44,000 | 0 | 3,000 | 47,000 |
| 180 | Ash Street | Clay | MD Residential | 4878 | 1600 | | 600 | 200 | 2400 | 2478 | 26,000 | 0 | 3,000 | 29,000 |
| 181 | Ash Street | Clay | MD Residential | 6581 | 1600 | | 600 | 200 | 2400 | 4181 | 44,000 | 0 | 3,000 | 47,000 |
| 190 | Ash Street | Clay | MD Residential | 4326 | 1600 | | 600 | 200 | 2400 | 1926 | 20,000 | 0 | 3,000 | 23,000 |
| 191 | Ash Street | Clay | MD Residential | 6560 | 1600 | | 600 | 200 | 2400 | 4160 | 43,000 | 0 | 3,000 | 46,000 |
| 100 | Ash-Acorn Connec | Clay | MD Residential | 3127 | 1600 | | 600 | 200 | 2400 | 727 | 8,000 | 0 | 3,000 | 11,000 |

| Add-ress | Street | Soil | Land Use | Area (ft²) | Roof (ft²) | Parking (ft²) | Drive-ways (ft²) | Patios (ft²) | Impervious (ft²) | Pervious (ft²) | Landscaping (1/99 $) | Parking (1/99 $) | Driveway (1/99 $) | Total (1/99 $) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 101 | Ash-Acorn Connec | Clay | MD Residential | 3180 | 1600 | | 600 | 200 | 2400 | 780 | 9,000 | 0 | 3,000 | 12,000 |
| 111 | Ash-Acorn Connec | Clay | MD Residential | 3039 | 1600 | | 600 | 200 | 2400 | 639 | 7,000 | 0 | 3,000 | 10,000 |
| 121 | Ash-Acorn Connec | Clay | MD Residential | 3157 | 1600 | | 600 | 200 | 2400 | 757 | 8,000 | 0 | 3,000 | 11,000 |
| 131 | Ash-Acorn Connec | Clay | MD Residential | 2994 | 1600 | | 600 | 200 | 2400 | 594 | 7,000 | 0 | 3,000 | 10,000 |
| 141 | Ash-Acorn Connec | Clay | MD Residential | 3086 | 1600 | | 600 | 200 | 2400 | 686 | 8,000 | 0 | 3,000 | 11,000 |
| 150 | Ash-Acorn Connec | Clay | MD Residential | 4739 | 1600 | | 600 | 200 | 2400 | 2339 | 25,000 | 0 | 3,000 | 28,000 |
| 151 | Ash-Acorn Connec | Clay | MD Residential | 3157 | 1600 | | 600 | 200 | 2400 | 757 | 8,000 | 0 | 3,000 | 11,000 |
| 154 | Ash-Acorn Connec | Clay | MD Residential | 5648 | 1600 | | 600 | 200 | 2400 | 3248 | 34,000 | 0 | 3,000 | 37,000 |
| 155 | Ash-Acorn Connec | Clay | MD Residential | 3109 | 1600 | | 600 | 200 | 2400 | 709 | 8,000 | 0 | 3,000 | 11,000 |
| 161 | Ash-Acorn Connec | Clay | MD Residential | 3089 | 1600 | | 600 | 200 | 2400 | 689 | 8,000 | 0 | 3,000 | 11,000 |
| 165 | Ash-Acorn Connec | Clay | MD Residential | 3149 | 1600 | | 600 | 200 | 2400 | 749 | 8,000 | 0 | 3,000 | 11,000 |
| 166 | Ash-Acorn Connec | Clay | MD Residential | 5648 | 1600 | | 600 | 200 | 2400 | 3248 | 34,000 | 0 | 3,000 | 37,000 |
| 170 | Ash-Acorn Connec | Clay | MD Residential | 4630 | 1600 | | 600 | 200 | 2400 | 2230 | 23,000 | 0 | 3,000 | 26,000 |
| 171 | Ash-Acorn Connec | Clay | MD Residential | 3349 | 1600 | | 600 | 200 | 2400 | 949 | 10,000 | 0 | 3,000 | 13,000 |
| 180 | Ash-Acorn Connec | Clay | MD Residential | 4818 | 1600 | | 600 | 200 | 2400 | 2418 | 25,000 | 0 | 3,000 | 28,000 |
| 181 | Ash-Acorn Connec | Clay | MD Residential | 2948 | 1600 | | 600 | 200 | 2400 | 548 | 6,000 | 0 | 3,000 | 9,000 |
| 190 | Ash-Acorn Connec | Clay | MD Residential | 4551 | 1600 | | 600 | 200 | 2400 | 2151 | 23,000 | 0 | 3,000 | 26,000 |
| 191 | Ash-Acorn Connec | Clay | MD Residential | 2686 | 1600 | | 600 | 200 | 2400 | 286 | 3,000 | 0 | 3,000 | 6,000 |
| 100 | Birch Avenue | Clay | MD Residential | 6469 | 1600 | | 600 | 200 | 2400 | 4069 | 42,000 | 0 | 3,000 | 45,000 |
| 101 | Birch Avenue | Clay | MD Residential | 6554 | 1600 | | 600 | 200 | 2400 | 4154 | 43,000 | 0 | 3,000 | 46,000 |
| 110 | Birch Avenue | Clay | MD Residential | 6477 | 1600 | | 600 | 200 | 2400 | 4077 | 42,000 | 0 | 3,000 | 45,000 |
| 111 | Birch Avenue | Clay | MD Residential | 6522 | 1600 | | 600 | 200 | 2400 | 4122 | 43,000 | 0 | 3,000 | 46,000 |
| 112 | Birch Avenue | Clay | MD Residential | 6484 | 1600 | | 600 | 200 | 2400 | 4084 | 43,000 | 0 | 3,000 | 46,000 |
| 116 | Birch Avenue | Clay | MD Residential | 6492 | 1600 | | 600 | 200 | 2400 | 4092 | 43,000 | 0 | 3,000 | 46,000 |
| 120 | Birch Avenue | Clay | MD Residential | 6499 | 1600 | | 600 | 200 | 2400 | 4099 | 43,000 | 0 | 3,000 | 46,000 |
| 121 | Birch Avenue | Clay | MD Residential | 6490 | 1600 | | 600 | 200 | 2400 | 4090 | 43,000 | 0 | 3,000 | 46,000 |
| 131 | Birch Avenue | Clay | MD Residential | 6457 | 1600 | | 600 | 200 | 2400 | 4057 | 42,000 | 0 | 3,000 | 45,000 |
| 141 | Birch Avenue | Clay | MD Residential | 6425 | 1600 | | 600 | 200 | 2400 | 4025 | 42,000 | 0 | 3,000 | 45,000 |
| 151 | Birch Avenue | Clay | MD Residential | 6360 | 1600 | | 600 | 200 | 2400 | 3960 | 41,000 | 0 | 3,000 | 44,000 |
| 161 | Birch Avenue | Clay | MD Residential | 6328 | 1600 | | 600 | 200 | 2400 | 3928 | 41,000 | 0 | 3,000 | 44,000 |
| 180 | Birch Avenue | Clay | MD Residential | 6560 | 1600 | | 600 | 200 | 2400 | 4160 | 43,000 | 0 | 3,000 | 46,000 |
| 190 | Birch Avenue | Clay | MD Residential | 6568 | 1600 | | 600 | 200 | 2400 | 4168 | 43,000 | 0 | 3,000 | 46,000 |
| 101 | Cedar Street | Clay | MD Residential | 6572 | 1600 | | 600 | 200 | 2400 | 4172 | 43,000 | 0 | 3,000 | 46,000 |
| 111 | Cedar Street | Clay | MD Residential | 6580 | 1600 | | 600 | 200 | 2400 | 4180 | 44,000 | 0 | 3,000 | 47,000 |
| 121 | Cedar Street | Clay | MD Residential | 6588 | 1600 | | 600 | 200 | 2400 | 4188 | 44,000 | 0 | 3,000 | 47,000 |
| 131 | Cedar Street | Clay | MD Residential | 6595 | 1600 | | 600 | 200 | 2400 | 4195 | 44,000 | 0 | 3,000 | 47,000 |
| 141 | Cedar Street | Clay | MD Residential | 6603 | 1600 | | 600 | 200 | 2400 | 4203 | 44,000 | 0 | 3,000 | 47,000 |
| 181 | Cedar Street | Clay | MD Residential | 6663 | 1600 | | 600 | 200 | 2400 | 4263 | 44,000 | 0 | 3,000 | 47,000 |
| 191 | Cedar Street | Clay | MD Residential | 6671 | 1600 | | 600 | 200 | 2400 | 4271 | 44,000 | 0 | 3,000 | 47,000 |
| 100 | Elm Street | Clay | MD Residential | 6481 | 1600 | | 600 | 200 | 2400 | 4081 | 43,000 | 0 | 3,000 | 46,000 |
| 110 | Elm Street | Clay | MD Residential | 6448 | 1600 | | 600 | 200 | 2400 | 4048 | 42,000 | 0 | 3,000 | 45,000 |
| 120 | Elm Street | Clay | MD Residential | 6416 | 1600 | | 600 | 200 | 2400 | 4016 | 42,000 | 0 | 3,000 | 45,000 |
| 130 | Elm Street | Clay | MD Residential | 6384 | 1600 | | 600 | 200 | 2400 | 3984 | 42,000 | 0 | 3,000 | 45,000 |
| 140 | Elm Street | Clay | MD Residential | 6351 | 1600 | | 600 | 200 | 2400 | 3951 | 41,000 | 0 | 3,000 | 44,000 |
| 150 | Elm Street | Clay | MD Residential | 6319 | 1600 | | 600 | 200 | 2400 | 3919 | 41,000 | 0 | 3,000 | 44,000 |
| 160 | Elm Street | Clay | MD Residential | 6286 | 1600 | | 600 | 200 | 2400 | 3886 | 41,000 | 0 | 3,000 | 44,000 |

| Add-ress | Street | Soil | Land Use | Area ($ft^2$) | Roof ($ft^2$) | Parking ($ft^2$) | Drive-ways ($ft^2$) | Patios ($ft^2$) | Impervious ($ft^2$) | Pervious ($ft^2$) | Landscaping (1/99 $) | Parking (1/99 $) | Driveway (1/99 $) | Total (1/99 $) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 170 | Elm Street | Clay | MD Residential | 6254 | 1600 | | 600 | 200 | 2400 | 3854 | 40,000 | 0 | 3,000 | 43,000 |
| 106 | Forest Avenue | Clay | MD Residential | 6428 | 1600 | | 600 | 200 | 2400 | 4028 | 42,000 | 0 | 3,000 | 45,000 |
| 101 | Main Street | Clay | MD Residential | 4993 | 1600 | | 600 | 200 | 2400 | 2593 | 27,000 | 0 | 3,000 | 30,000 |
| 111 | Main Street | Clay | MD Residential | 5154 | 1600 | | 600 | 200 | 2400 | 2754 | 29,000 | 0 | 3,000 | 32,000 |
| 120 | Main Street | Clay | MD Residential | 6770 | 1600 | | 600 | 200 | 2400 | 4370 | 45,000 | 0 | 3,000 | 48,000 |
| 140 | Main Street | Clay | MD Residential | 6636 | 1600 | | 600 | 200 | 2400 | 4236 | 44,000 | 0 | 3,000 | 47,000 |
| 141 | Main Street | Clay | MD Residential | 6323 | 1600 | | 600 | 200 | 2400 | 3923 | 41,000 | 0 | 3,000 | 44,000 |
| 150 | Main Street | Clay | MD Residential | 4939 | 1600 | | 600 | 200 | 2400 | 2539 | 27,000 | 0 | 3,000 | 30,000 |
| 151 | Main Street | Clay | MD Residential | 6323 | 1600 | | 600 | 200 | 2400 | 3923 | 41,000 | 0 | 3,000 | 44,000 |
| 100 | Street A | Clay | MD Residential | 5072 | 1600 | | 600 | 200 | 2400 | 2672 | 28,000 | 0 | 3,000 | 31,000 |
| 101 | Street A | Clay | MD Residential | 4644 | 1600 | | 600 | 200 | 2400 | 2244 | 24,000 | 0 | 3,000 | 27,000 |
| 120 | Street A | Clay | MD Residential | 5072 | 1600 | | 600 | 200 | 2400 | 2672 | 28,000 | 0 | 3,000 | 31,000 |
| 121 | Street A | Clay | MD Residential | 4789 | 1600 | | 600 | 200 | 2400 | 2389 | 25,000 | 0 | 3,000 | 28,000 |
| 141 | Street A | Clay | MD Residential | 4934 | 1600 | | 600 | 200 | 2400 | 2534 | 27,000 | 0 | 3,000 | 30,000 |
| 161 | Street A | Clay | MD Residential | 5079 | 1600 | | 600 | 200 | 2400 | 2679 | 28,000 | 0 | 3,000 | 31,000 |
| 100 | Street B | Clay | MD Residential | 4787 | 1600 | | 600 | 200 | 2400 | 2387 | 25,000 | 0 | 3,000 | 28,000 |
| 101 | Street B | Clay | MD Residential | 4953 | 1600 | | 600 | 200 | 2400 | 2553 | 27,000 | 0 | 3,000 | 30,000 |
| 121 | Street B | Clay | MD Residential | 4953 | 1600 | | 600 | 200 | 2400 | 2553 | 27,000 | 0 | 3,000 | 30,000 |
| 140 | Street B | Clay | MD Residential | 4787 | 1600 | | 600 | 200 | 2400 | 2387 | 25,000 | 0 | 3,000 | 28,000 |
| 100 | Street C | Clay | MD Residential | 5609 | 1600 | | 600 | 200 | 2400 | 3209 | 34,000 | 0 | 3,000 | 37,000 |
| 101 | Street C | Clay | MD Residential | 4737 | 1600 | | 600 | 200 | 2400 | 2337 | 25,000 | 0 | 3,000 | 28,000 |
| 120 | Street C | Clay | MD Residential | 5609 | 1600 | | 600 | 200 | 2400 | 3209 | 34,000 | 0 | 3,000 | 37,000 |
| 141 | Street C | Clay | MD Residential | 4888 | 1600 | | 600 | 200 | 2400 | 2488 | 26,000 | 0 | 3,000 | 29,000 |
| 100 | Street D | Clay | MD Residential | 5254 | 1600 | | 600 | 200 | 2400 | 2854 | 30,000 | 0 | 3,000 | 33,000 |
| 101 | Street D | Clay | MD Residential | 5461 | 1600 | | 600 | 200 | 2400 | 3061 | 32,000 | 0 | 3,000 | 35,000 |
| 120 | Street D | Clay | MD Residential | 5254 | 1600 | | 600 | 200 | 2400 | 2854 | 30,000 | 0 | 3,000 | 33,000 |
| 141 | Street D | Clay | MD Residential | 5461 | 1600 | | 600 | 200 | 2400 | 3061 | 32,000 | 0 | 3,000 | 35,000 |
| 101 | Street E | Clay | MD Residential | 5192 | 1600 | | 600 | 200 | 2400 | 2792 | 29,000 | 0 | 3,000 | 32,000 |
| 100 | Sycamore Street | Clay | MD Residential | 6480 | 1600 | | 600 | 200 | 2400 | 4080 | 42,000 | 0 | 3,000 | 45,000 |
| 101 | Sycamore Street | Clay | MD Residential | 6511 | 1600 | | 600 | 200 | 2400 | 4111 | 43,000 | 0 | 3,000 | 46,000 |
| 110 | Sycamore Street | Clay | MD Residential | 6460 | 1600 | | 600 | 200 | 2400 | 4060 | 42,000 | 0 | 3,000 | 45,000 |
| 111 | Sycamore Street | Clay | MD Residential | 6712 | 1600 | | 600 | 200 | 2400 | 4312 | 45,000 | 0 | 3,000 | 48,000 |
| 120 | Sycamore Street | Clay | MD Residential | 6439 | 1600 | | 600 | 200 | 2400 | 4039 | 42,000 | 0 | 3,000 | 45,000 |
| 121 | Sycamore Street | Clay | MD Residential | 6470 | 1600 | | 600 | 200 | 2400 | 4070 | 42,000 | 0 | 3,000 | 45,000 |
| 130 | Sycamore Street | Clay | MD Residential | 6419 | 1600 | | 600 | 200 | 2400 | 4019 | 42,000 | 0 | 3,000 | 45,000 |
| 131 | Sycamore Street | Clay | MD Residential | 6492 | 1600 | | 600 | 200 | 2400 | 4092 | 43,000 | 0 | 3,000 | 46,000 |
| 140 | Sycamore Street | Clay | MD Residential | 6399 | 1600 | | 600 | 200 | 2400 | 3999 | 42,000 | 0 | 3,000 | 45,000 |
| 141 | Sycamore Street | Clay | MD Residential | 6514 | 1600 | | 600 | 200 | 2400 | 4114 | 43,000 | 0 | 3,000 | 46,000 |
| 150 | Sycamore Street | Clay | MD Residential | 6378 | 1600 | | 600 | 200 | 2400 | 3978 | 41,000 | 0 | 3,000 | 44,000 |
| 151 | Sycamore Street | Clay | MD Residential | 6536 | 1600 | | 600 | 200 | 2400 | 4136 | 43,000 | 0 | 3,000 | 46,000 |
| 156 | Sycamore Street | Clay | MD Residential | 6358 | 1600 | | 600 | 200 | 2400 | 3958 | 41,000 | 0 | 3,000 | 44,000 |
| 160 | Sycamore Street | Clay | MD Residential | 6337 | 1600 | | 600 | 200 | 2400 | 3937 | 41,000 | 0 | 3,000 | 44,000 |
| 161 | Sycamore Street | Clay | MD Residential | 6558 | 1600 | | 600 | 200 | 2400 | 4158 | 43,000 | 0 | 3,000 | 46,000 |
| 165 | Sycamore Street | Clay | MD Residential | 6580 | 1600 | | 600 | 200 | 2400 | 4180 | 44,000 | 0 | 3,000 | 47,000 |
| 166 | Sycamore Street | Clay | MD Residential | 6317 | 1600 | | 600 | 200 | 2400 | 3917 | 41,000 | 0 | 3,000 | 44,000 |
| 170 | Sycamore Street | Clay | MD Residential | 6296 | 1600 | | 600 | 200 | 2400 | 3896 | 41,000 | 0 | 3,000 | 44,000 |

| Address | Street | Soil | Land Use | Area ($ft^2$) | Roof ($ft^2$) | Parking ($ft^2$) | Drive-ways ($ft^2$) | Patios ($ft^2$) | Impervious ($ft^2$) | Pervious ($ft^2$) | Landscaping (1/99 $) | Parking (1/99 $) | Driveway (1/99 $) | Total (1/99 $) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 171 | Sycamore Street | Clay | MD Residential | 5931 | 1600 | | 600 | 200 | 2400 | 3531 | 37,000 | 0 | 3,000 | 40,000 |
| 180 | Sycamore Street | Clay | MD Residential | 6276 | 1600 | | 600 | 200 | 2400 | 3876 | 40,000 | 0 | 3,000 | 43,000 |
| 181 | Sycamore Street | Clay | MD Residential | 5744 | 1600 | | 600 | 200 | 2400 | 3344 | 35,000 | 0 | 3,000 | 38,000 |
| 190 | Sycamore Street | Clay | MD Residential | 6255 | 1600 | | 600 | 200 | 2400 | 3855 | 40,000 | 0 | 3,000 | 43,000 |
| 191 | Sycamore Street | Clay | MD Residential | 6274 | 1600 | | 600 | 200 | 2400 | 3874 | 40,000 | 0 | 3,000 | 43,000 |
| 193 | Sycamore Street | Clay | MD Residential | 5919 | 1600 | | 600 | 200 | 2400 | 3519 | 37,000 | 0 | 3,000 | 40,000 |
| 101 | Ashmount Street | Rock | MD Residential | 6649 | 1600 | | 600 | 200 | 2400 | 4249 | 44,000 | 0 | 3,000 | 47,000 |
| 110 | Ashmount Street | Rock | MD Residential | 5611 | 1600 | | 600 | 200 | 2400 | 3211 | 34,000 | 0 | 3,000 | 37,000 |
| 120 | Ashmount Street | Rock | MD Residential | 5524 | 1600 | | 600 | 200 | 2400 | 3124 | 33,000 | 0 | 3,000 | 36,000 |
| 130 | Ashmount Street | Rock | MD Residential | 6461 | 1600 | | 600 | 200 | 2400 | 4061 | 42,000 | 0 | 3,000 | 45,000 |
| 140 | Ashmount Street | Rock | MD Residential | 6805 | 1600 | | 600 | 200 | 2400 | 4405 | 46,000 | 0 | 3,000 | 49,000 |
| 150 | Ashmount Street | Rock | MD Residential | 6624 | 1600 | | 600 | 200 | 2400 | 4224 | 44,000 | 0 | 3,000 | 47,000 |
| 156 | Ashmount Street | Rock | MD Residential | 6875 | 1600 | | 600 | 200 | 2400 | 4475 | 47,000 | 0 | 3,000 | 50,000 |
| 158 | Ashmount Street | Rock | MD Residential | 6554 | 1600 | | 600 | 200 | 2400 | 4154 | 43,000 | 0 | 3,000 | 46,000 |
| 160 | Ashmount Street | Rock | MD Residential | 6693 | 1600 | | 600 | 200 | 2400 | 4293 | 45,000 | 0 | 3,000 | 48,000 |
| 170 | Ashmount Street | Rock | MD Residential | 6533 | 1600 | | 600 | 200 | 2400 | 4133 | 43,000 | 0 | 3,000 | 46,000 |
| 180 | Ashmount Street | Rock | MD Residential | 6461 | 1600 | | 600 | 200 | 2400 | 4061 | 42,000 | 0 | 3,000 | 45,000 |
| 190 | Ashmount Street | Rock | MD Residential | 5691 | 1600 | | 600 | 200 | 2400 | 3291 | 34,000 | 0 | 3,000 | 37,000 |
| 161 | Main Street | Rock | MD Residential | 6323 | 1600 | | 600 | 200 | 2400 | 3923 | 41,000 | 0 | 3,000 | 44,000 |
| 130 | Street A | Rock | MD Residential | 5072 | 1600 | | 600 | 200 | 2400 | 2672 | 28,000 | 0 | 3,000 | 31,000 |
| 170 | Street A | Rock | MD Residential | 5072 | 1600 | | 600 | 200 | 2400 | 2672 | 28,000 | 0 | 3,000 | 31,000 |
| 190 | Street A | Rock | MD Residential | 5072 | 1600 | | 600 | 200 | 2400 | 2672 | 28,000 | 0 | 3,000 | 31,000 |
| 141 | Street B | Rock | MD Residential | 4953 | 1600 | | 600 | 200 | 2400 | 2553 | 27,000 | 0 | 3,000 | 30,000 |
| 160 | Street B | Rock | MD Residential | 4787 | 1600 | | 600 | 200 | 2400 | 2387 | 25,000 | 0 | 3,000 | 28,000 |
| 180 | Street B | Rock | MD Residential | 4787 | 1600 | | 600 | 200 | 2400 | 2387 | 25,000 | 0 | 3,000 | 28,000 |
| 181 | Street B | Rock | MD Residential | 4953 | 1600 | | 600 | 200 | 2400 | 2553 | 27,000 | 0 | 3,000 | 30,000 |
| 190 | Street B | Rock | MD Residential | 4787 | 1600 | | 600 | 200 | 2400 | 2387 | 25,000 | 0 | 3,000 | 28,000 |
| 191 | Street B | Rock | MD Residential | 4953 | 1600 | | 600 | 200 | 2400 | 2553 | 27,000 | 0 | 3,000 | 30,000 |
| 160 | Street C | Rock | MD Residential | 5609 | 1600 | | 600 | 200 | 2400 | 3209 | 34,000 | 0 | 3,000 | 37,000 |
| 161 | Street C | Rock | MD Residential | 5039 | 1600 | | 600 | 200 | 2400 | 2639 | 28,000 | 0 | 3,000 | 31,000 |
| 171 | Street C | Rock | MD Residential | 5189 | 1600 | | 600 | 200 | 2400 | 2789 | 29,000 | 0 | 3,000 | 32,000 |
| 190 | Street C | Rock | MD Residential | 5609 | 1600 | | 600 | 200 | 2400 | 3209 | 34,000 | 0 | 3,000 | 37,000 |
| 191 | Street C | Rock | MD Residential | 5340 | 1600 | | 600 | 200 | 2400 | 2940 | 31,000 | 0 | 3,000 | 34,000 |
| 180 | Street D | Rock | MD Residential | 5254 | 1600 | | 600 | 200 | 2400 | 2854 | 30,000 | 0 | 3,000 | 33,000 |
| 181 | Street D | Rock | MD Residential | 5461 | 1600 | | 600 | 200 | 2400 | 3061 | 32,000 | 0 | 3,000 | 35,000 |
| 190 | Street D | Rock | MD Residential | 5254 | 1600 | | 600 | 200 | 2400 | 2854 | 30,000 | 0 | 3,000 | 33,000 |
| 191 | Street D | Rock | MD Residential | 5461 | 1600 | | 600 | 200 | 2400 | 3061 | 32,000 | 0 | 3,000 | 35,000 |
| 100 | Street E | Rock | MD Residential | 6520 | 1600 | | 600 | 200 | 2400 | 4120 | 43,000 | 0 | 3,000 | 46,000 |
| 120 | Street E | Rock | MD Residential | 6520 | 1600 | | 600 | 200 | 2400 | 4120 | 43,000 | 0 | 3,000 | 46,000 |
| 151 | Street E | Rock | MD Residential | 5363 | 1600 | | 600 | 200 | 2400 | 2963 | 31,000 | 0 | 3,000 | 34,000 |
| 171 | Street E | Rock | MD Residential | 5533 | 1600 | | 600 | 200 | 2400 | 3133 | 33,000 | 0 | 3,000 | 36,000 |
| 190 | Street E | Rock | MD Residential | 6520 | 1600 | | 600 | 200 | 2400 | 4120 | 43,000 | 0 | 3,000 | 46,000 |
| 191 | Street E | Rock | MD Residential | 5704 | 1600 | | 600 | 200 | 2400 | 3304 | 35,000 | 0 | 3,000 | 38,000 |
| 126 | Birch Avenue | Silt | MD Residential | 6507 | 1600 | | 600 | 200 | 2400 | 4107 | 43,000 | 0 | 3,000 | 46,000 |
| 130 | Birch Avenue | Silt | MD Residential | 6515 | 1600 | | 600 | 200 | 2400 | 4115 | 43,000 | 0 | 3,000 | 46,000 |
| 136 | Birch Avenue | Silt | MD Residential | 6522 | 1600 | | 600 | 200 | 2400 | 4122 | 43,000 | 0 | 3,000 | 46,000 |

| Address | Street | Soil | Land Use | Area ($ft^2$) | Roof ($ft^2$) | Parking ($ft^2$) | Drive-ways ($ft^2$) | Patios ($ft^2$) | Impervious ($ft^2$) | Pervious ($ft^2$) | Landscaping (1/99 $) | Parking (1/99 $) | Driveway (1/99 $) | Total (1/99 $) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 140 | Birch Avenue | Silt | MD Residential | 6530 | 1600 | | 600 | 200 | 2400 | 4130 | 43,000 | 0 | 3,000 | 46,000 |
| 150 | Birch Avenue | Silt | MD Residential | 6537 | 1600 | | 600 | 200 | 2400 | 4137 | 43,000 | 0 | 3,000 | 46,000 |
| 160 | Birch Avenue | Silt | MD Residential | 6545 | 1600 | | 600 | 200 | 2400 | 4145 | 43,000 | 0 | 3,000 | 46,000 |
| 170 | Birch Avenue | Silt | MD Residential | 6552 | 1600 | | 600 | 200 | 2400 | 4152 | 43,000 | 0 | 3,000 | 46,000 |
| 171 | Birch Avenue | Silt | MD Residential | 6345 | 1600 | | 600 | 200 | 2400 | 3945 | 41,000 | 0 | 3,000 | 44,000 |
| 181 | Birch Avenue | Silt | MD Residential | 6939 | 1600 | | 600 | 200 | 2400 | 4539 | 47,000 | 0 | 3,000 | 50,000 |
| 191 | Birch Avenue | Silt | MD Residential | 7911 | 1600 | | 600 | 200 | 2400 | 5511 | 57,000 | 0 | 3,000 | 60,000 |
| 193 | Birch Avenue | Silt | MD Residential | 5095 | 1600 | | 600 | 200 | 2400 | 2695 | 28,000 | 0 | 3,000 | 31,000 |
| 151 | Cedar Street | Silt | MD Residential | 6610 | 1600 | | 600 | 200 | 2400 | 4210 | 44,000 | 0 | 3,000 | 47,000 |
| 155 | Cedar Street | Silt | MD Residential | 6618 | 1600 | | 600 | 200 | 2400 | 4218 | 44,000 | 0 | 3,000 | 47,000 |
| 161 | Cedar Street | Silt | MD Residential | 6625 | 1600 | | 600 | 200 | 2400 | 4225 | 44,000 | 0 | 3,000 | 47,000 |
| 165 | Cedar Street | Silt | MD Residential | 6633 | 1600 | | 600 | 200 | 2400 | 4233 | 44,000 | 0 | 3,000 | 47,000 |
| 171 | Cedar Street | Silt | MD Residential | 6641 | 1600 | | 600 | 200 | 2400 | 4241 | 44,000 | 0 | 3,000 | 47,000 |
| 175 | Cedar Street | Silt | MD Residential | 6648 | 1600 | | 600 | 200 | 2400 | 4248 | 44,000 | 0 | 3,000 | 47,000 |
| 179 | Cedar Street | Silt | MD Residential | 6656 | 1600 | | 600 | 200 | 2400 | 4256 | 44,000 | 0 | 3,000 | 47,000 |
| 101 | Elm Street | Silt | MD Residential | 6663 | 1600 | | 600 | 200 | 2400 | 4263 | 44,000 | 0 | 3,000 | 47,000 |
| 111 | Elm Street | Silt | MD Residential | 6667 | 1600 | | 600 | 200 | 2400 | 4267 | 44,000 | 0 | 3,000 | 47,000 |
| 121 | Elm Street | Silt | MD Residential | 6671 | 1600 | | 600 | 200 | 2400 | 4271 | 44,000 | 0 | 3,000 | 47,000 |
| 131 | Elm Street | Silt | MD Residential | 6676 | 1600 | | 600 | 200 | 2400 | 4276 | 45,000 | 0 | 3,000 | 48,000 |
| 141 | Elm Street | Silt | MD Residential | 6680 | 1600 | | 600 | 200 | 2400 | 4280 | 45,000 | 0 | 3,000 | 48,000 |
| 151 | Elm Street | Silt | MD Residential | 6684 | 1600 | | 600 | 200 | 2400 | 4284 | 45,000 | 0 | 3,000 | 48,000 |
| 176 | Elm Street | Silt | MD Residential | 6070 | 1600 | | 600 | 200 | 2400 | 3670 | 38,000 | 0 | 3,000 | 41,000 |
| 180 | Elm Street | Silt | MD Residential | 6675 | 1600 | | 600 | 200 | 2400 | 4275 | 45,000 | 0 | 3,000 | 48,000 |
| 181 | Elm Street | Silt | MD Residential | 6688 | 1600 | | 600 | 200 | 2400 | 4288 | 45,000 | 0 | 3,000 | 48,000 |
| 190 | Elm Street | Silt | MD Residential | 6941 | 1600 | | 600 | 200 | 2400 | 4541 | 47,000 | 0 | 3,000 | 50,000 |
| 191 | Elm Street | Silt | MD Residential | 6693 | 1600 | | 600 | 200 | 2400 | 4293 | 45,000 | 0 | 3,000 | 48,000 |
| 193 | Elm Street | Silt | MD Residential | 4843 | 1600 | | 600 | 200 | 2400 | 2443 | 26,000 | 0 | 3,000 | 29,000 |
| 195 | Elm Street | Silt | MD Residential | 4131 | 1600 | | 600 | 200 | 2400 | 1731 | 18,000 | 0 | 3,000 | 21,000 |
| 201 | Elm Street | Silt | MD Residential | 6416 | 1600 | | 600 | 200 | 2400 | 4016 | 42,000 | 0 | 3,000 | 45,000 |
| 221 | Elm Street | Silt | MD Residential | 6106 | 1600 | | 600 | 200 | 2400 | 3706 | 39,000 | 0 | 3,000 | 42,000 |
| 231 | Elm Street | Silt | MD Residential | 6452 | 1600 | | 600 | 200 | 2400 | 4052 | 42,000 | 0 | 3,000 | 45,000 |
| 241 | Elm Street | Silt | MD Residential | 6627 | 1600 | | 600 | 200 | 2400 | 4227 | 44,000 | 0 | 3,000 | 47,000 |
| 244 | Elm Street | Silt | MD Residential | 6706 | 1600 | | 600 | 200 | 2400 | 4306 | 45,000 | 0 | 3,000 | 48,000 |
| 250 | Elm Street | Silt | MD Residential | 6894 | 1600 | | 600 | 200 | 2400 | 4494 | 47,000 | 0 | 3,000 | 50,000 |
| 251 | Elm Street | Silt | MD Residential | 6665 | 1600 | | 600 | 200 | 2400 | 4265 | 44,000 | 0 | 3,000 | 47,000 |
| 254 | Elm Street | Silt | MD Residential | 6256 | 1600 | | 600 | 200 | 2400 | 3856 | 40,000 | 0 | 3,000 | 43,000 |
| 260 | Elm Street | Silt | MD Residential | 6865 | 1600 | | 600 | 200 | 2400 | 4465 | 46,000 | 0 | 3,000 | 49,000 |
| 261 | Elm Street | Silt | MD Residential | 6682 | 1600 | | 600 | 200 | 2400 | 4282 | 45,000 | 0 | 3,000 | 48,000 |
| 270 | Elm Street | Silt | MD Residential | 6463 | 1600 | | 600 | 200 | 2400 | 4063 | 42,000 | 0 | 3,000 | 45,000 |
| 274 | Elm Street | Silt | MD Residential | 6886 | 1600 | | 600 | 200 | 2400 | 4486 | 47,000 | 0 | 3,000 | 50,000 |
| 280 | Elm Street | Silt | MD Residential | 6909 | 1600 | | 600 | 200 | 2400 | 4509 | 47,000 | 0 | 3,000 | 50,000 |
| 281 | Elm Street | Silt | MD Residential | 6699 | 1600 | | 600 | 200 | 2400 | 4299 | 45,000 | 0 | 3,000 | 48,000 |
| 290 | Elm Street | Silt | MD Residential | 6765 | 1600 | | 600 | 200 | 2400 | 4365 | 45,000 | 0 | 3,000 | 48,000 |
| 291 | Elm Street | Silt | MD Residential | 6716 | 1600 | | 600 | 200 | 2400 | 4316 | 45,000 | 0 | 3,000 | 48,000 |
| 100 | Forest Avenue | Silt | MD Residential | 6312 | 1600 | | 600 | 200 | 2400 | 3912 | 41,000 | 0 | 3,000 | 44,000 |
| 101 | Forest Avenue | Silt | MD Residential | 7572 | 1600 | | 600 | 200 | 2400 | 5172 | 54,000 | 0 | 3,000 | 57,000 |

| Address | Street | Soil | Land Use | Area ($ft^2$) | Roof ($ft^2$) | Parking ($ft^2$) | Drive-ways ($ft^2$) | Patios ($ft^2$) | Impervious ($ft^2$) | Pervious ($ft^2$) | Landscaping (1/99 $) | Parking (1/99 $) | Driveway (1/99 $) | Total (1/99 $) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 110 | Forest Avenue | Silt | MD Residential | 6424 | 1600 | | 600 | 200 | 2400 | 4024 | 42,000 | 0 | 3,000 | 45,000 |
| 111 | Forest Avenue | Silt | MD Residential | 6971 | 1600 | | 600 | 200 | 2400 | 4571 | 48,000 | 0 | 3,000 | 51,000 |
| 120 | Forest Avenue | Silt | MD Residential | 6294 | 1600 | | 600 | 200 | 2400 | 3894 | 41,000 | 0 | 3,000 | 44,000 |
| 130 | Forest Avenue | Silt | MD Residential | 6313 | 1600 | | 600 | 200 | 2400 | 3913 | 41,000 | 0 | 3,000 | 44,000 |
| 140 | Forest Avenue | Silt | MD Residential | 6353 | 1600 | | 600 | 200 | 2400 | 3953 | 41,000 | 0 | 3,000 | 44,000 |
| 141 | Forest Avenue | Silt | MD Residential | 6998 | 1600 | | 600 | 200 | 2400 | 4598 | 48,000 | 0 | 3,000 | 51,000 |
| 150 | Forest Avenue | Silt | MD Residential | 6333 | 1600 | | 600 | 200 | 2400 | 3933 | 41,000 | 0 | 3,000 | 44,000 |
| 151 | Forest Avenue | Silt | MD Residential | 6875 | 1600 | | 600 | 200 | 2400 | 4475 | 47,000 | 0 | 3,000 | 50,000 |
| 160 | Forest Avenue | Silt | MD Residential | 6372 | 1600 | | 600 | 200 | 2400 | 3972 | 41,000 | 0 | 3,000 | 44,000 |
| 161 | Forest Avenue | Silt | MD Residential | 6694 | 1600 | | 600 | 200 | 2400 | 4294 | 45,000 | 0 | 3,000 | 48,000 |
| 170 | Forest Avenue | Silt | MD Residential | 6392 | 1600 | | 600 | 200 | 2400 | 3992 | 42,000 | 0 | 3,000 | 45,000 |
| 171 | Forest Avenue | Silt | MD Residential | 6619 | 1600 | | 600 | 200 | 2400 | 4219 | 44,000 | 0 | 3,000 | 47,000 |
| 180 | Forest Avenue | Silt | MD Residential | 8120 | 1600 | | 600 | 200 | 2400 | 5720 | 59,000 | 0 | 3,000 | 62,000 |
| 181 | Forest Avenue | Silt | MD Residential | 6724 | 1600 | | 600 | 200 | 2400 | 4324 | 45,000 | 0 | 3,000 | 48,000 |
| 186 | Forest Avenue | Silt | MD Residential | 6312 | 1600 | | 600 | 200 | 2400 | 3912 | 41,000 | 0 | 3,000 | 44,000 |
| 190 | Forest Avenue | Silt | MD Residential | 6079 | 1600 | | 600 | 200 | 2400 | 3679 | 38,000 | 0 | 3,000 | 41,000 |
| 191 | Forest Avenue | Silt | MD Residential | 6599 | 1600 | | 600 | 200 | 2400 | 4199 | 44,000 | 0 | 3,000 | 47,000 |
| 200 | Forest Avenue | Silt | MD Residential | 6558 | 1600 | | 600 | 200 | 2400 | 4158 | 43,000 | 0 | 3,000 | 46,000 |
| 201 | Forest Avenue | Silt | MD Residential | 6500 | 1600 | | 600 | 200 | 2400 | 4100 | 43,000 | 0 | 3,000 | 46,000 |
| 205 | Forest Avenue | Silt | MD Residential | 6389 | 1600 | | 600 | 200 | 2400 | 3989 | 42,000 | 0 | 3,000 | 45,000 |
| 210 | Forest Avenue | Silt | MD Residential | 6562 | 1600 | | 600 | 200 | 2400 | 4162 | 43,000 | 0 | 3,000 | 46,000 |
| 211 | Forest Avenue | Silt | MD Residential | 6266 | 1600 | | 600 | 200 | 2400 | 3866 | 40,000 | 0 | 3,000 | 43,000 |
| 220 | Forest Avenue | Silt | MD Residential | 6566 | 1600 | | 600 | 200 | 2400 | 4166 | 43,000 | 0 | 3,000 | 46,000 |
| 221 | Forest Avenue | Silt | MD Residential | 6326 | 1600 | | 600 | 200 | 2400 | 3926 | 41,000 | 0 | 3,000 | 44,000 |
| 230 | Forest Avenue | Silt | MD Residential | 6570 | 1600 | | 600 | 200 | 2400 | 4170 | 43,000 | 0 | 3,000 | 46,000 |
| 231 | Forest Avenue | Silt | MD Residential | 6133 | 1600 | | 600 | 200 | 2400 | 3733 | 39,000 | 0 | 3,000 | 42,000 |
| 240 | Forest Avenue | Silt | MD Residential | 6575 | 1600 | | 600 | 200 | 2400 | 4175 | 43,000 | 0 | 3,000 | 46,000 |
| 241 | Forest Avenue | Silt | MD Residential | 6025 | 1600 | | 600 | 200 | 2400 | 3625 | 38,000 | 0 | 3,000 | 41,000 |
| 250 | Forest Avenue | Silt | MD Residential | 6579 | 1600 | | 600 | 200 | 2400 | 4179 | 44,000 | 0 | 3,000 | 47,000 |
| 251 | Forest Avenue | Silt | MD Residential | 6193 | 1600 | | 600 | 200 | 2400 | 3793 | 40,000 | 0 | 3,000 | 43,000 |
| 261 | Forest Avenue | Silt | MD Residential | 6379 | 1600 | | 600 | 200 | 2400 | 3979 | 41,000 | 0 | 3,000 | 44,000 |
| 270 | Forest Avenue | Silt | MD Residential | 6583 | 1600 | | 600 | 200 | 2400 | 4183 | 44,000 | 0 | 3,000 | 47,000 |
| 271 | Forest Avenue | Silt | MD Residential | 6169 | 1600 | | 600 | 200 | 2400 | 3769 | 39,000 | 0 | 3,000 | 42,000 |
| 280 | Forest Avenue | Silt | MD Residential | 6587 | 1600 | | 600 | 200 | 2400 | 4187 | 44,000 | 0 | 3,000 | 47,000 |
| 281 | Forest Avenue | Silt | MD Residential | 5411 | 1600 | | 600 | 200 | 2400 | 3011 | 31,000 | 0 | 3,000 | 34,000 |
| 290 | Forest Avenue | Silt | MD Residential | 3196 | 1600 | | 600 | 200 | 2400 | 796 | 9,000 | 0 | 3,000 | 12,000 |
| 291 | Forest Avenue | Silt | MD Residential | 5894 | 1600 | | 600 | 200 | 2400 | 3494 | 36,000 | 0 | 3,000 | 39,000 |
| 293 | Forest Avenue | Silt | MD Residential | 3230 | 1600 | | 600 | 200 | 2400 | 830 | 9,000 | 0 | 3,000 | 12,000 |
| 121 | Main Street | Silt | MD Residential | 5200 | 1600 | | 600 | 200 | 2400 | 2800 | 29,000 | 0 | 3,000 | 32,000 |
| 125 | Center Street | Silt | School | 8600 | 0 | 8600 | 0 | 0 | 8600 | 0 | 0 | 41,000 | 0 | 41,000 |
| 100 | Walnut Street | Silt | School | 97601 | 69080 | 0 | 0 | 0 | 69080 | 28521 | 725,000 | 0 | 0 | 25,000 |
| 101 | Walnut Street | Silt | School | 43206 | 0 | 43206 | 0 | 0 | 43206 | 0 | 0 | 203,000 | 0 | 203,000 |
| | | | | | | | | | | | 14,498,000 | 2,028,000 | 969,000 | 17,495,000 |

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### *6.4.4 Summary of costs for each right-of-way*

A preliminary estimate of the right-of-way costs of development is obtained by:

1) Extracting the length and area attributes for each object using the "streets" theme from the ArcView database;
2) Multiplying the unit costs found in Table 6-22 for 50 ft rights-of-way; Table 6-23 for 60 ft rights-of-way, and Table 6-24 for 70 ft rights-of-way by the area of each right-of-way parcel.

The right-of-way cost data are presented in Table 6-29. Total paving costs for the development are $2.3 million. Total opportunity costs for the area within the right-of-way are $5.9 million. The total landscaping costs for the rights of way are $884,000.

**Table 6-29. Right-of-Way Costs**

| Street Name | RW width, (ft) | RW length, (ft) | Area ($ft^2$) | Paving Cost (1/99 $) | Opportunity Cost (1/99 $) | Landscaping Cost (1/99 $) | Total Cost (1/99 $) |
|---|---|---|---|---|---|---|---|
| Acorn Street | 50 | 1640 | 81990 | 114,000 | 286,000 | 42,000.00 | 442,000 |
| Alpine Street | 50 | 1125 | 56272 | 78,000 | 197,000 | 29,000.00 | 304,000 |
| Ash Street | 50 | 1205 | 60251 | 84,000 | 211,000 | 31,000.00 | 326,000 |
| Ash-Acorn Connector | 50 | 844 | 42214 | 59,000 | 148,000 | 22,000.00 | 229,000 |
| Ashmount Street | 50 | 870 | 43492 | 61,000 | 152,000 | 22,000.00 | 235,000 |
| Ashmount Street ext. | 50 | 1620 | 80981 | 112,000 | 283,000 | 41,000.00 | 436,000 |
| Aspen Street | 50 | 851 | 42537 | 59,000 | 149,000 | 22,000.00 | 230,000 |
| Birch Avenue | 50 | 2574 | 128701 | 178,000 | 449,000 | 65,000.00 | 692,000 |
| Cedar Street | 50 | 2899 | 144940 | 201,000 | 506,000 | 73,000.00 | 780,000 |
| Center Street | 60 | 1124 | 67445 | 92,000 | 236,000 | 29,000.00 | 357,000 |
| Elm Street | 50 | 2639 | 131944 | 183,000 | 461,000 | 67,000.00 | 711,000 |
| Forest Avenue | 50 | 2622 | 131119 | 182,000 | 458,000 | 66,000.00 | 706,000 |
| Highland Street | 50 | 831 | 41568 | 58,000 | 145,000 | 21,000.00 | 224,000 |
| Main Street | 70 | 2741 | 191895 | 230,000 | 670,000 | 124,000.00 | 1,024,000 |
| Maple Street | 50 | 2153 | 107667 | 149,000 | 376,000 | 55,000.00 | 580,000 |
| Oak Street | 50 | 1751 | 87540 | 122,000 | 306,000 | 44,000.00 | 472,000 |
| Street A | 50 | 490 | 24491 | 34,000 | 86,000 | 13,000.00 | 133,000 |
| Street B | 50 | 465 | 23267 | 33,000 | 82,000 | 12,000.00 | 127,000 |
| Street C | 50 | 517 | 25829 | 36,000 | 91,000 | 13,000.00 | 140,000 |
| Street D | 50 | 415 | 20756 | 29,000 | 73,000 | 11,000.00 | 113,000 |
| Street E | 50 | 397 | 19875 | 28,000 | 70,000 | 10,000.00 | 108,000 |
| stub between Elm and Forest | 50 | 519 | 25951 | 36,000 | 91,000 | 14,000.00 | 141,000 |
| Sycamore Street | 50 | 1086 | 54281 | 76,000 | 190,000 | 28,000.00 | 294,000 |
| Walnut Street | 50 | 1167 | 58349 | 81,000 | 204,000 | 30,000.00 | 315,000 |
| Total | | | 1693357 | 2,315,000 | 5,920,000 | 884,000 | 9,119,000 |

## 6.5 Estimated cost of BMP controls

The following sections describe the methodology used to determine runoff volumes, evaluate the calculated difference in volume between the predevelopment and post development scenarios, and lay out the procedure for estimating unit costs/gal of selected controls for the optimization process.

### 6.5.1 Determination of runoff volumes using SCS method

Each developed land use is assigned a curve number (CN) based upon work done by the Soil Conservation Service (1986). The initial abstraction, or available storage is estimated by the following equation:

$$I_a = \frac{200}{CN} - 2 \tag{6-3}$$

The final list of 10 permeable and 16 impermeable candidate land uses, with their expected effectiveness as measured by their curve number (CN), and the associated initial abstraction in inches, calculated using equation 6.3 are shown in Table 6-30. The CNs range from 25 – 98. The initial abstraction associated with a CN of 25 is 6.00 in of precipitation. Making this land impervious increases the CN to 98 with an associated initial abstraction of only 0.04 in, a major loss of infiltration capacity. Using unit costs in $/ft$^2$, and having determined the appropriate abstraction, it is possible to convert the control option costs to $/gal., which is done in the last four columns of Table 6-30. These values are unique to the soil type heading the column. Unit costs expressed as $/gal are useful for comparative purposes, as will be seen later.

### 6.5.2 Breakdown of calculated volumes per function

A functional analysis within each land use and soil classification is performed by adding the total amounts of area for the functions of roof, lawns, driveways, and parking (for non-right-of-way uses), and streets, curbs, parking, sidewalks, and lawns for rights-of-way areas. Volumes of developed runoff can then be calculated by multiplying the initial abstraction by the appropriate area. Predevelopment runoff can be calculated using the composite curve number 63.07 for the area prior to development, determining an initial abstraction for each soil group, and multiplying this again by the area as done for the developed volumes. The result of this analysis is found in Table 6-31.

The functions are then compared across land uses by computing the difference between the sum of the function's pre-development and post-development storage volumes. This is plotted as a bar chart in Figure 6-6. The greatest impact by far is from streets and roofs, with roughly equal values of storage volume reduction. Patios are insignificant in this analysis. Lawns actually add a great deal of storage, somewhat offsetting the drastic reductions from roofs and streets. Driveways and parking lots result in smaller reductions in volume; however, because it is concentrated over smaller areas, the local impact may be great.

Table 6-30. SCS Hydrologic Classifications, and Calculation of Unit Storage Values (SCS, 1986)

| | | Cover Description | | Curve Number | | | | Initial Abstraction (in.) | | | | Unit cost (1/99 $/ft$^2$) | Unit Cost (1/99 $/gal) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | Type | Cover type and hydrologic condition | ID | A | B | C | D | A | B | C | D | | A | B | C | D |
| 1 | Permeable | Aspen-mountain brush mixture: Fair:30%–70% ground cover | Aspen F | 28 | 48 | 57 | 63 | 5.14 | 2.17 | 1.51 | 1.17 | 2.00 | 0.62 | 1.48 | 2.13 | 2.73 |
| 2 | Permeable | Aspen-mountain brush mixture: Good: >70% ground cover | Aspen G | 25 | 30 | 41 | 48 | 6.00 | 4.67 | 2.88 | 2.17 | 3.00 | 0.80 | 1.03 | 1.67 | 2.22 |
| 1 | Impervious | Driveway | Driveway 1 | 98 | 98 | 98 | 98 | 0.04 | 0.04 | 0.04 | 0.04 | 0.23 | 9.21 | 9.21 | 9.21 | 9.21 |
| 2 | Impervious | Driveway-porous pavement | Driveway 2 | 70 | 80 | 85 | 87 | 0.86 | 0.50 | 0.35 | 0.30 | 0.25 | 0.47 | 0.80 | 1.13 | 1.34 |
| 3 | Permeable | Lawns, pasture, grassland: Fair condition (grass cover 50%–75%) | Grass F | 49 | 69 | 79 | 84 | 2.08 | 0.90 | 0.53 | 0.38 | 0.81 | 0.63 | 1.45 | 2.45 | 3.42 |
| 4 | Permeable | Lawns, pasture, grassland: Good condition (grass cover >75%) | Grass G | 39 | 61 | 74 | 80 | 3.13 | 1.28 | 0.70 | 0.50 | 1.03 | 0.53 | 1.29 | 2.35 | 3.30 |
| 5 | Permeable | Lawns, pasture, grassland: Poor condition (grass cover < 50%) | Grass P | 68 | 79 | 86 | 89 | 0.94 | 0.53 | 0.33 | 0.25 | 0.70 | 1.19 | 2.12 | 3.45 | 4.55 |
| 6 | Impervious | Parking | Parking 1 | 98 | 98 | 98 | 98 | 0.04 | 0.04 | 0.04 | 0.04 | 0.23 | 9.21 | 9.21 | 9.21 | 9.21 |
| 4 | Impervious | Porous parking 1 | Parking 2 | 61 | 75 | 83 | 87 | 1.28 | 0.67 | 0.41 | 0.30 | 0.25 | 0.31 | 0.60 | 0.98 | 1.34 |
| 5 | Impervious | Porous parking 2 | Parking 3 | 46 | 65 | 77 | 82 | 2.35 | 1.08 | 0.60 | 0.44 | 0.26 | 0.18 | 0.39 | 0.71 | 0.97 |
| 6 | Impervious | Porous parking 3 | Parking 4 | 36 | 55 | 67 | 72 | 3.56 | 1.64 | 0.99 | 0.78 | 0.28 | 0.13 | 0.27 | 0.46 | 0.58 |
| 7 | Impervious | Patio | Patio 1 | 95 | 95 | 95 | 95 | 0.11 | 0.11 | 0.11 | 0.11 | 0.19 | 2.89 | 2.89 | 2.89 | 2.89 |
| 8 | Impervious | Porous patio | Patio 2 | 76 | 85 | 89 | 91 | 0.63 | 0.35 | 0.25 | 0.20 | 0.19 | 0.49 | 0.88 | 1.25 | 1.57 |
| 9 | Impervious | Roof | Roof 1 | 95 | 95 | 95 | 95 | 0.11 | 0.11 | 0.11 | 0.11 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 10 | Impervious | Roof with detention | Roof 2 | 85 | 85 | 85 | 85 | 0.35 | 0.35 | 0.35 | 0.35 | 1.50 | 6.82 | 6.82 | 6.82 | 6.82 |
| 11 | Impervious | Sidewalks | Sidewalk 1 | 98 | 98 | 98 | 98 | 0.04 | 0.04 | 0.04 | 0.04 | 0.19 | 7.44 | 7.44 | 7.44 | 7.44 |
| 12 | Impervious | Sidewalks with porous materials | Sidewalk 2 | 70 | 80 | 85 | 87 | 0.86 | 0.50 | 0.35 | 0.30 | 0.19 | 0.36 | 0.62 | 0.88 | 1.04 |
| 13 | Permeable | Storage-offsite in infiltration/detention basins | Storage | 15 | 20 | 35 | 40 | 11.33 | 8.00 | 3.71 | 3.00 | 5.00 | 0.71 | 1.00 | 2.16 | 2.67 |
| 14 | Impervious | Street with curb and gutter | Street 1 | 98 | 98 | 98 | 98 | 0.04 | 0.04 | 0.04 | 0.04 | 0.25 | 9.77 | 9.77 | 9.77 | 9.77 |
| 15 | Impervious | Street with curb and gutter and porous pavement | Street 2 | 70 | 80 | 85 | 87 | 0.86 | 0.50 | 0.35 | 0.30 | 0.26 | 0.49 | 0.84 | 1.19 | 1.41 |
| 16 | Impervious | Street with swales | Street 3 | 76 | 85 | 89 | 91 | 0.63 | 0.35 | 0.25 | 0.20 | 0.27 | 0.68 | 1.22 | 1.74 | 2.17 |
| 17 | Impervious | Street with swales and porous pavement | Street 4 | 61 | 75 | 83 | 87 | 1.28 | 0.67 | 0.41 | 0.30 | 0.28 | 0.35 | 0.67 | 1.09 | 1.49 |
| 18 | Permeable | Swales 1 | Swales 1 | 46 | 65 | 77 | 82 | 2.35 | 1.08 | 0.60 | 0.44 | 3.00 | 2.05 | 4.47 | 8.06 | 10.96 |
| 19 | Permeable | Swales 2 | Swales 2 | 29 | 50 | 62 | 67 | 4.90 | 2.00 | 1.23 | 0.99 | 6.00 | 1.97 | 4.81 | 7.85 | 9.77 |
| 20 | Permeable | Woods:Fair: Woods are grazed but not burned, and some forest litter | Woods F | 36 | 60 | 73 | 79 | 3.56 | 1.33 | 0.74 | 0.53 | 0.80 | 0.36 | 0.96 | 1.73 | 2.41 |
| 21 | Permeable | Woods:Good: Woods without grazing, and adequate litter and brush | Woods G | 25 | 55 | 70 | 77 | 6.00 | 1.64 | 0.86 | 0.60 | 1.40 | 0.37 | 1.37 | 2.62 | 3.76 |

Table 6-31. Calculation of Developed and Predevelopment Stormwater Volumes

| | | | | | Developed | | Total Dev. | Undev. | | Total Undev. |
|---|---|---|---|---|---|---|---|---|---|---|
| Land Use | Function | B | D, Total | Area, Total | Volume, B | Volume, D | Volume | B | D | Volume |
| | | ($ft^2$) | ($ft^2$) | ($ft^2$) | ($ft^3$) | ($ft^3$) | ($ft^3$) | ($ft^3$) | ($ft^3$) | ($ft^3$) |
| Apartments | Roof | 46,927 | 0 | 46,927 | 412 | 0 | 412 | 4,580 | 0 | 4,580 |
| | Parking | 75,083 | 0 | 75,083 | 255 | 0 | 255 | 7,327 | 0 | 7,327 |
| | Driveway | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Lawns | 40,670 | 0 | 40,670 | 4,334 | 0 | 4,334 | 3,969 | 0 | 3,969 |
| Commercial | Roof | 95,132 | 57,707 | 152,839 | 834 | 506 | 1,341 | 9,284 | 49 | 9,333 |
| | Parking | 44,810 | 259,868 | 304,678 | 152 | 884 | 1,036 | 4,373 | 86 | 4,459 |
| | Driveway | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Lawns | 6,839 | 16,714 | 23,553 | 729 | 696 | 1,425 | 667 | 68 | 735 |
| MD Residential | Roof | 140,800 | 267,200 | 408,000 | 1,235 | 2,344 | 3,579 | 13,741 | 229 | 13,969 |
| | Parking | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Driveway | 52,800 | 100,200 | 153,000 | 180 | 341 | 520 | 5,153 | 33 | 5,186 |
| | Lawns | 353,666 | 538,755 | 892,420 | 37,686 | 22,448 | 60,134 | 34,514 | 2,191 | 36,705 |
| | Patio | 17,600 | 33,400 | 51,000 | 154 | 293 | 447 | | | 0 |
| LD Residential | Roof | 102,000 | 0 | 102,000 | 895 | 0 | 895 | 9,954 | 0 | 9,954 |
| | Parking | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Driveway | 40,800 | 0 | 40,800 | 139 | 0 | 139 | 3,982 | 0 | 3,982 |
| | Lawns | 491,233 | 0 | 491,233 | 52,344 | 0 | 52,344 | 47,939 | 0 | 47,939 |
| | Patio | 20,400 | 0 | 20,400 | 179 | 0 | 179 | | | 0 |
| School | Roof | 69,080 | 0 | 69,080 | 606 | 0 | 606 | 6,742 | 0 | 6,742 |
| | Parking | 51,806 | 0 | 51,806 | 176 | 0 | 176 | 5,056 | 0 | 5,056 |
| | Driveway | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Lawns | 28,521 | 0 | 28,521 | 3,039 | 0 | 3,039 | 2,783 | 0 | 2,783 |
| Streets | | | | | | | | | | |
| 50 | ROW | 659,728 | 774,288 | 1,434,016 | | | | | | |
| | Street with curb and gutter | 105,556 | 123,886 | 229,443 | 359 | 421 | 780 | 10,301 | 41 | 10,342 |
| | Parking | 105,556 | 123,886 | 229,443 | 359 | 421 | 780 | 10,301 | 41 | 10,342 |
| | Sidewalks | 105,556 | 123,886 | 229,443 | 359 | 421 | 780 | 10,301 | 41 | 10,342 |
| | curb | 52,778 | 61,943 | 114,721 | 180 | 211 | 390 | 5,151 | 21 | 5,171 |
| | Lawns | 52,778 | 61,943 | 114,721 | 3,952 | 1,966 | 5,918 | 5,151 | 192 | 5,343 |
| 60 | ROW | 87,540 | 0 | 87,540 | | | | | | |
| | Street with curb and gutter | 11,672 | 0 | 11,672 | 40 | 0 | 40 | 1,139 | 0 | 1,139 |
| | Parking | 23,344 | 0 | 23,344 | 79 | 0 | 79 | 2,278 | 0 | 2,278 |
| | Sidewalks | 11,672 | 0 | 11,672 | 40 | 0 | 40 | 1,139 | 0 | 1,139 |
| | Curb | 5,836 | 0 | 5,836 | 20 | 0 | 20 | 570 | 0 | 570 |
| | Lawns | 5,836 | 0 | 5,836 | 437 | 0 | 437 | 570 | 0 | 570 |
| 70 | ROW | 13,195 | 189,531 | 202,726 | | | | | | |
| | Street with curb and gutter | 1,508 | 21,661 | 23,169 | 5 | 74 | 79 | 147 | 7 | 154 |
| | Parking | 3,016 | 43,321 | 46,337 | 10 | 147 | 158 | 294 | 14 | 309 |
| | Sidewalks | 1,508 | 21,661 | 23,169 | 5 | 74 | 79 | 147 | 7 | 154 |
| | Curb | 754 | 10,830 | 11,584 | 3 | 37 | 39 | 74 | 4 | 77 |
| | Lawns | 754 | 10,830 | 11,584 | 56 | 344 | 400 | 74 | 34 | 107 |
| | Total | | | 1,724,282 | | | 140,882 | | | 21,0758 |

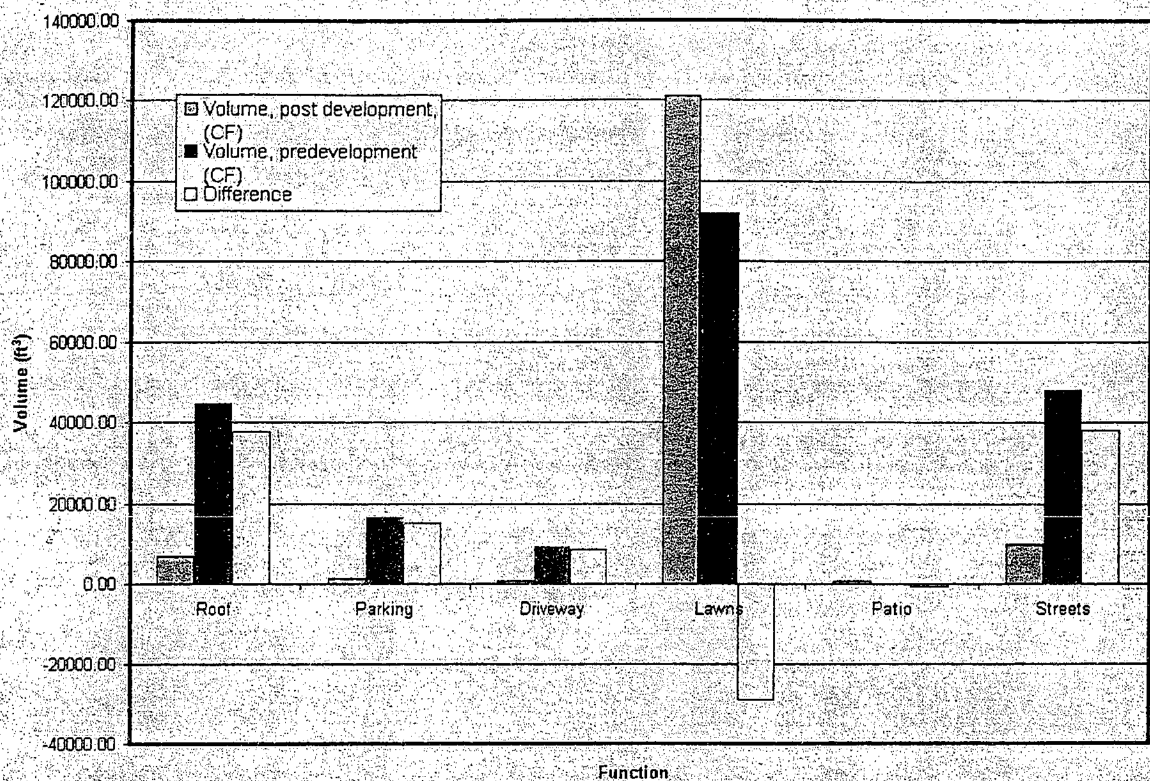


**Figure 6-6. Allocation of available storage for initial abstraction and land use.**

### *6.5.3 Estimated unit costs of various functional land use options*

BMP control costs are estimated in $/ft$^2$. These costs are assumed incremental costs over and above the costs of conventional systems. These unit cost estimates are preliminary in that the proper definition of cost depends upon alternatives that provide "equivalent" levels of service. For example, consider the following three options for a 6,000 ft$^2$ lawn:

- Conventional lawn with a sprinkling system
- 3,000 ft$^2$ of conventional lawn and 3,000 ft$^2$ of forest
- 2,000 ft$^2$ of conventional lawn; 2,000 ft$^2$ of forest; and 2,000 ft$^2$ of swales

While it is possible to estimate the cost of each of these three options, the customer must view these options as providing the same level of service for them to be considered equivalent. If the customer strongly prefers the conventional lawn, then it is inaccurate to select other options based on lower cost if they are not perceived to be equivalent. Further work is needed to provide a more accurate assessment of equivalent landscapes. For this example customers are assumed to simply select the least costly combination of BMP controls.

Using the procedures developed in section 6.4, unit costs for controls determined by Table 6-30 were used for eight different land-use model: low and medium density residential; commercial; school; apartment; and 50, 60, and 70 ft rights-of-way. The unit costs, which include opportunity costs, are listed in Table 6-32. An alternative analysis was performed which excluded the effect of opportunity costs. These unit costs are presented in Table 6-33.

**Table 6-32. Calculation of Unit Costs for Controls, Including Land Opportunity Costs**

| ID | LD Res. (1/99 $/ft$^2$) | MD Res. (1/99 $/ft$^2$) | Commer. (1/99 $/ft$^2$) | School (1/99 $/ft$^2$) | Apartm't (1/99 $/ft$^2$) | RW50 (1/99 $/ft$^2$) | RW60 (1/99 $/ft$^2$) | RW70 (1/99 $/ft$^2$) |
|---|---|---|---|---|---|---|---|---|
| Aspen F | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| Aspen G | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 |
| Driveway 1 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 |
| Driveway 2 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 |
| Grass F | 0.60 | 0.60 | 2.12 | 2.49 | 1.22 | 0.60 | 0.60 | 0.60 |
| Grass G | 0.69 | 0.69 | 2.18 | 2.56 | 1.29 | 0.69 | 0.69 | 0.69 |
| Grass P | 0.49 | 0.49 | 2.01 | 2.38 | 1.11 | 0.49 | 0.49 | 0.49 |
| Parking 1 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 |
| Parking 2 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 |
| Parking 3 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 |
| Parking 4 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 |
| Patio 1 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 |
| Patio 2 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 |
| Roof 1 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Roof 2 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 |
| Sidewalk 1 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 |
| Sidewalk 2 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 |
| Storage | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 |
| Street 1 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.24 |
| Street 2 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 |
| Street 3 | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 | 0.27 |
| Street 4 | 0.28 | 0.29 | 0.28 | 0.28 | 0.28 | 0.28 | 0.29 | 0.28 |
| Swales 1 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 |
| Swales 2 | 6.00 | 6.00 | 6.00 | 6.00 | 6.00 | 6.00 | 6.00 | 6.00 |
| Woods F | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 |
| Woods G | 1.40 | 1.40 | 1.40 | 1.40 | 1.40 | 1.40 | 1.40 | 1.40 |

Table 6-33. Calculation of Unit Costs for Controls, Excluding Land Opportunity Costs

| ID | LD Res. (1/99 $/ft²) | MD Res. (1/99 $/ft²) | Commer. (1/99 $/ft²) | School (1/99 $/ft²) | Apartm't (1/99 $/ft²) | RW50 (1/99 $/ft²) | RW60 (1/99 $/ft²) | RW70 (1/99 $/ft²) |
|---|---|---|---|---|---|---|---|---|
| Aspen F | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| Aspen G | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 |
| Driveway 1 | 0.06 | 0.23 | 0.23 | 0.23 | 0.23 | 0.06 | 0.06 | 0.06 |
| Driveway 2 | 0.08 | 0.25 | 0.25 | 0.25 | 0.25 | 0.08 | 0.08 | 0.08 |
| Grass F | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 |
| Grass G | 0.34 | 0.37 | 0.32 | 0.32 | 0.32 | 0.34 | 0.34 | 0.34 |
| Grass P | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 | 0.14 |
| Parking 1 | 0.06 | 0.23 | 0.23 | 0.23 | 0.23 | 0.06 | 0.06 | 0.06 |
| Parking 2 | 0.08 | 0.25 | 0.25 | 0.25 | 0.25 | 0.08 | 0.08 | 0.08 |
| Parking 3 | 0.09 | 0.26 | 0.26 | 0.26 | 0.26 | 0.09 | 0.09 | 0.09 |
| Parking 4 | 0.11 | 0.28 | 0.28 | 0.28 | 0.28 | 0.11 | 0.11 | 0.11 |
| Patio 1 | 0.02 | 0.19 | 0.19 | 0.19 | 0.19 | 0.02 | 0.02 | 0.02 |
| Patio 2 | 0.02 | 0.19 | 0.19 | 0.19 | 0.19 | 0.02 | 0.02 | 0.02 |
| Roof 1 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Roof 2 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 | 1.50 |
| Sidewalk 1 | 0.02 | 0.19 | 0.19 | 0.19 | 0.19 | 0.02 | 0.02 | 0.02 |
| Sidewalk 2 | 0.02 | 0.19 | 0.19 | 0.19 | 0.19 | 0.02 | 0.02 | 0.02 |
| Storage | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 |
| Street 1 | 0.07 | 0.25 | 0.25 | 0.25 | 0.25 | 0.07 | 0.07 | 0.07 |
| Street 2 | 0.09 | 0.26 | 0.26 | 0.26 | 0.26 | 0.09 | 0.08 | 0.08 |
| Street 3 | 0.09 | 0.27 | 0.27 | 0.27 | 0.27 | 0.09 | 0.10 | 0.10 |
| Street 4 | 0.10 | 0.28 | 0.28 | 0.28 | 0.28 | 0.10 | 0.11 | 0.11 |
| Swales 1 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 | 3.00 |
| Swales 2 | 6.00 | 6.00 | 6.00 | 6.00 | 6.00 | 6.00 | 6.00 | 6.00 |
| Woods F | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 |
| Woods G | 1.40 | 1.40 | 1.40 | 1.40 | 1.40 | 1.40 | 1.40 | 1.40 |

The reasonableness of these estimates can be judged by comparing them to the unit cost of storage systems reported in the literature; first converting them to unit costs in terms of $/gal for a given soil type, as done in Table 6-30. Storage costs described in chapter 5 of this report range from about $0.03 to $15.12/ gal (Table 6-34, is calculated using the equations from Chapter 5, obtaining a cost, then dividing the cost by the volume in gal.). Using $5.00/ ft² in Table 6-32 and 6-33, the results range from $0.71–$2.67/gal, well within an acceptable range. Costs for swales were estimated based upon the range of equation 4.13. Costs for aspen and woods are estimated based upon typical landscaping costs, and comparing the computed $/gal unit costs with others for reasonableness. The incremental cost for roofed area is based on the added cost of directing this runoff toward an appropriate permeable area, and again was checked for reasonableness.

Table 6-34. Range of Costs for Storage

| Volume (1,000 gal.) | EPA CSO storage (1/99 $/gal) | Detention Basin (1/99 $/gal) | Retention Basin (1/99 $/gal) | Infiltration Basin (1/99 $/gal) |
|---|---|---|---|---|
| 1 | 15.12 | 0.47 | 0.34 | 0.45 |
| 10 | 10.13 | 0.23 | 0.19 | 0.22 |
| 100 | 6.79 | 0.11 | 0.11 | 0.11 |
| 1,000 | 4.55 | 0.06 | 0.06 | 0.05 |
| 10,000 | 3.05 | 0.03 | 0.03 | 0.03 |

## 6.6 Results of BMP Optimization for Happy Acres

The detailed results of the optimization can be found in the companion report Heaney et al. (1998c). The optimal total system cost, including land opportunity costs for Happy Acres is $4.2 million (calibrated to the Denver/Boulder, CO area). The total system cost, neglecting opportunity costs is $3.9 million. This represents approximately 15%–19 % of the total $26.6 million investment overall (not including buildings).

Direct comparison to the values obtained here for the micro-storm analysis with those for the major storm analysis cannot be done, as it is normally expected that the total costs for micro-storm drainage control would be less than that for minor and major storms ($915,000 and $1.21 million, respectively). A key issue here is that the allocation of a fixed percentage of costs to stormwater control needs to be evaluated further. This percentage is essentially unknown at present.

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# Chapter 7

## Summary and Conclusions

Cost estimation procedures for urban stormwater systems were primarily developed prior to 1980. Simple equations using one or two explanatory variables were, and still are being used to estimate costs. Modern hardware and software enable a move to data driven approaches and a focus on developing good databases for developing cost estimates. Equations are a very restrictive way to present information and should only be used for simple summaries. The availability of computerized cost databases from companies such as R.S. Means provide a very good source of information about current unit costs. In order to significantly advance the state of the art in cost effectiveness modeling, unit cost data need to be directly linked to process-simulators as demonstrated in chapter 5. This spreadsheet model can be adapted to a wide variety of physical settings and used to do a comprehensive evaluation of the nature of system costs and their relative importance. Five scenarios were evaluated to illustrate the use of this model. However, the variety of what-if analyses is virtually limitless. There are well over 1,000 variables for this 106 acre storm drainage design, thus, the number of combinations is very large. While this process-oriented approach is a major improvement over existing practices, it is still severely limited in that it only does what-if analysis and cannot systematically do what's-best optimization analysis. Currently, such an approach using intelligent search techniques is in development and this method has successfully been applied to optimization of water distribution systems (Lippai et al., 1999).

The application of GIS technology allows for a more thorough, parcel based approach to the analysis of water quality impacts during micro-storms from land use changes and development. Although the hydrologic model used here is limited (as with the rational model used in the sewer design model for the major and minor storms), it is apparent that many impacts could then be traced directly to their origin

This initial exploration into storm drainage design cost estimation suggests the following gaps in knowledge to be addressed by additional research:

1. A process-oriented approach to cost-effectiveness evaluations is essential. Curve fitting approaches to cost estimation based on as-built systems are too aggregate and the databases too inconsistent to provide the reliable estimates needed to enhance our understanding of the underlying cause-effect relationships.
2. The unit cost data provided by companies such as R.S. Means are a valuable source of the necessary cost data and should be an integral part of the overall cost-effectiveness evaluations.
3. The spreadsheet model presented in this report should be expanded to implement intelligent search techniques to determine optimal design.
4. An accurate representation of the system hydraulics is essential to meaningful system optimization. While the spreadsheet can be used for simple hydraulic analysis, it is essential to link the spreadsheet with hydraulic analyzers such as SWMM so that the

hydraulics can be done more accurately. We have already done such linkages in looking at water distribution systems by linking the optimizer with EPANET (Lippai et al., 1999).

5. The Rational Method to estimate peak inflows to pipes is archaic and should be replaced by data centered approaches. For example, the cost of this sewer system design depends heavily on the assumed travel time to the sewer inlet. Yet, this value is difficult to estimate accurately.
6. Conventional storm sewer design should also check how the system performs during small storms when lower velocities might prevail and cause sediment accumulations in the sewers.
7. The analysis needs to be expanded to include the effect of storage on the system design. However, before evaluating storage, it is imperative to use more realistic storm hydrographs and not continue to compound our ignorance by using simple extensions of the Rational Method.
8. The method needs to be expanded to include onsite controls such as infiltration. Such an analysis is not simple since storage routing is required at the parcel level in addition to evaluating larger storage systems.
9. A database of flow and quality monitoring for small (100 acres or less) catchments is needed to evaluate actual system response for small drainage areas. These catchments can be used for overall cost-effectiveness evaluations.
10. The benefits of urban stormwater systems need to be quantified. Flood damages are relatively easy to estimate. However, stormwater quality control benefits are more elusive.
11. The overall system evaluation should include structural and non-structural BMPs as well as conventional storm drainage systems.
12. The incidence of benefits and costs of alternative drainage systems needs to be quantified. Residents who control their problems on site should receive fair credit for reducing system cost.
13. Downstream receiving water impacts should be included in the evaluations.
14. A combined sewer design should be evaluated and its cost apportioned among wastewater and stormwater. The effect of providing additional storage in the combined sewer should be evaluated.
15. The cost optimization should be refined to take into account both the broader land use optimization, and to allocate the costs down to each land use, and to each parcel. Combined with GIS, this analysis should be done for several different scenarios (micro-storms, minor storms, and major storms).
16. The impact of streets and parking as integral parts of the urban stormwater system needs to be evaluated. Streets and parking comprise the majority of the directly connected impervious areas for stormwater systems. Hence, they are a major source of the problem. However, they also comprise an essential element of the stormwater management system, especially during periods of very high runoff when the sewers are overloaded. A significant part of the cost of streets and parking is for drainage. This cost needs to be included in the overall cost of stormwater management systems. A preliminary attempt has been made here to quantify these impacts in micro-storms. More work at identifying these impacts, and assessing an allocated, true cost of alleviating these impacts to these sources is essential for containment.

# Environment regulations don't drive up home prices

**Contrary to many opinions, the influence of environmental regulations on prices of new housing is only negligible.**

*provided by Cornell University*

Contrary to popular belief, buyers of new homes should know that the costs of supporting environmental protection don't boost the prices of new houses, a Cornell University housing expert concludes. Higher prices seem to be much more likely the result of larger homes and more amenities.

The average cost of a new home in the United States shot up 32 percent in the past decade, and some people blame much of this increase on environmental regulations. But a new Cornell study finds no empirical evidence to support these claims.

"We find that the costs of complying with the regulations have only a negligible impact on the average price of a new house," says Joseph Laquatra, associate professor of design and environmental analysis at Cornell. "Rather, we conclude from strong evidence that higher prices are much more likely the result of building bigger homes with more amenities."

Builders and developers must comply with federal regulations that include the Clean Water Act, Federal Water Pollution Control Act and the Endangered Species Act. They and others have long assumed that these environmental regulations, which seek to improve air and water quality and protect biodiversity, have thwarted development and driven the costs of new homes beyond what first-time buyers can afford.

"While the goals of most protection programs enjoy broad support, the implementation of these initiatives is all too often unduly cumbersome," said H. Daniel Pincus, the 1997 president of the National Association of Home Builders, in the NAHB publication *Building the American Dream.* "Unnecessary and redundant regulations add more than 20 percent to the cost of building a home in many areas," he said.

"There are certainly anecdotal horror stories in which environmental protection has been used to stop particular developments," says Laquatra. "But we couldn't find evidence in the numerous studies on this issue that demonstrate a direct relationship between environmental regulations and house prices."

Laquatra and independent scholar Gregory Potter conducted a comprehensive review of more than 100 studies that looked at housing affordability and environmental regulations; they also analyzed transcripts from two focus groups Laquatra conducted in Seattle and in Gainesville, FL. Their report was published in the (April) Earth Day 2000 issue of the Electronic Green Journal (Issue 12).

In the focus groups, Laquatra moderated discussions about loss of species, housing affordability, equity, property rights, regulatory burdens and similar issues with builders, developers, environmental regulators, affordable-housing and environmental advocates, congressional staffers, students of construction management and faculty in academic construction-management programs.

"Interestingly, housing affordability was not a primary concern in the focus groups. And in the literature review, we found no evidence that higher housing prices are due to the costs of complying with environmental regulations. Rather, strong evidence points to a drop in home ownership rates during the 1980s being due to changes in tastes and lifestyles and not economic hardship," says Laquatra.

Home ownership, which is now at the highest rate in US history, includes almost 68 percent of American households. Yet the median price of a typical new home tripled between 1977 and 1997. In 1989, for example, the average price of a new home was 148,800. By 1999, it was $195,700.

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"We also found evidence that the public is overwhelmingly in favor of environmental protection and thinks the government should be spending even more on protecting the environment," Laquatra says. "Although builders may incur some costs in complying with the codes, on a national basis these costs do not significantly affect the cost of a new house."

In related work, Laquatra is now leading a study funded by the Cornell Community and Rural Development Institute on "Building a Balance: Housing Affordability, Environmental Protection, and Smart Land Use Decisions." In collaboration with faculty from Cornell's College of Agriculture and Life Sciences, Laquatra is conducting focus groups in four communities across New York state to find out how the communities feel about growth issues. ET

*For information on Joe Laquatra, please see http://DEA.human.cornell.edu/DEA/Laquatra.html. For a copy of the fact sheet Building A Balance: Housing Affordability and Environmental Protection, please see http://www.nahb.com/hot_topics/balance_1.htm*

# The Issues Surrounding Development

Rates of population growth and housing development across the United States are creating pressures on communities to provide adequate infrastructure services for a growing population. Although the United States experienced a population increase of almost nine percent between 1990 and 1998, in New York State that figure was one percent. While population density in some areas of the state remains stable and in some areas is actually decreasing, other areas are facing increases in population density that result in rapid community changes with negative impacts associated with sprawl. These changes are forcing communities to think about planning issues in different ways. Increasingly, town boards must approach growth decisions with information about loss of open spaces and farmland, impacts on the quality of life, and the range of economic issues associated with development.

In New York State **Home Rule** or **Home Rule Authority** gives local governments the power to adopt laws that relate to their local property, affairs and government, such as laws that apply to land protection and development. Home Rule Authority is in addition to the powers that are specifically delegated to local governments by the legislature. Land use regulations like zoning ordinances are an example of Home Rule authority. The Municipal Home Rule Law authorizes local governments to adopt these kinds of land use regulations.

Typically, local officials review and approve a variety of isolated development proposals. The specific proposals come in all sizes and focus on housing units, commercial properties and industrial facilities. Generally these proposals must be reviewed without detailed knowledge of the public service cost and revenue benefits associated with them. This raises questions about actual service impacts of various kinds of development, typical revenue impacts of development, related multiplier effects on the local economy, and the associated tax impacts of these multiplier effects.

Moreover, local officials are regularly asked to help make development happen. Help may involve regulatory exceptions, loan guarantees, provision of infrastructure costs, and reduced tax payments. Local governments, particularly small and rural ones, often don't have the numbers or a way of totaling up the quantitative and qualitative impacts to make a solid decision that they feel comfortable with. For most local governments the big projects are the exception. A particular board member may see only one or two big projects during his or her tenure on the board of a smaller community, but that project may provide long-term impacts on the community. Having good, timely information and a framework to evaluate the impacts and to access need professional expertise is essential and crucial, especially for small communities to make good decisions.

**Smart Growth** and similar, if loosely defined concepts, are beginning to capture the public's imagination. Although there is no single consensus definition, a core concept of Smart Growth is that public policies should channel growth and development toward areas that are already under development as much as possible. Policies should aim to encourage high-density, mixed-use designs instead of low-density development, while reducing growth pressures on agricultural lands and open or undeveloped spaces. These policies avoid factors that characterize sprawl: a low-density floor-to-area ratio; unlimited outward extension; "leapfrog" development; single-use and single-story buildings; and car-dependent design. Sprawl typically occurs on the outskirts of cities or in rural areas between urban centers.

**Building a Balance: Housing Affordability, Environmental Protection, and Smart Land Use Decisions** is the title of a research project funded by the Community and Rural Development Institute at Cornell University. The goal of this project was to examine policies that focus on land use patterns and associated fiscal implications for local governments, as well as mechanisms for preserving open space and achieving goals related to environmental protection and housing affordability. This goal was achieved by conducting a series of focus groups in communities throughout New York State in which development-related concerns were expressed by town supervisors, county planning commissioners, mayors, school district officials, developers, farmers, environmental advocates, housing affordability advocates, and others. The focus groups demonstrated that common ground exists among groups that are often perceived to be in conflict with each other. The project has identified processes and tools to guide communities through development decisions in ways that facilitate open discussion without polarizing disputes among various interest groups.

Communities can grow and avoid sprawl without new legislation at the state level. Zoning and subdivision regulations, for example, can reflect a community's decisions about land resources, types of buildings, infill development, mixed-use and high-density development, and other issues. New developments that locate homes, stores, schools, offices, and public facilities within walking distance of each other will avoid congested roads and streets. Existing land use tools, such as the Purchase of Development Rights (PDR), can keep designated lands for agricultural purposes without denying farmers the economic gain they would realize from selling their property for development.

Issues surrounding development involve complex decisions by town boards; and local governments are assuming prominent roles in the formulation of growth policies for their communities. Town Board members and the general public can facilitate sound development decisions by approaching them in an informed manner that is sensitive to the needs of all parties in the development process. The fact sheets in this series were written with this objective in mind.

This fact sheet was prepared as part of the Cornell University project,
**Building a Balance: Housing Affordability, Environmental Protection, and Smart Land Use Decisions.**
Project members: Joseph Laquatra, Department of Design and Environmental Analysis; Patricia Baron Pollak, Department of Policy Analysis and Management; Nelson Bills, Michael Hattery, and David Kay, Local Government Program in the Department of Applied Economics and Management.

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# Building a Balance: Housing Affordability and Environmental Protection in the USA

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## Abstract

Current trends in household formation and housing development in the United States are creating pressures on communities to provide adequate infrastructure services for a growing population. Homeownership rates are the highest in history. All indications suggest this rate will continue to increase over the next few years. Builders and developers respond to this need by constructing housing units in suburban fringe and rural areas because of the availability of cheaper land and the lack of attractive sites in more urban areas. Environmental regulations are frequently cited as barriers to development and impediments to affordability. This paper reviews the literature of potential linkages between housing affordability and environmental protection and reports on a project in which focus groups were conducted with developers, environmental regulators, and others. Content analysis of focus group transcripts showed much agreement from various sides of the complicated and interconnected issues that are related to sustainable development.

## Introduction

Since enactment of the first major environmental legislation in the United States in 1972, an increasing number of laws have been passed for the purpose of improving air and water quality and protecting biodiversity. Although Americans agree environmental protection is essential (Dunlap, 1992), there is considerable controversy over what constitutes an acceptable level of regulation and how the economic burden of environmental regulation should be distributed (Branconi, 1996).

With escalating levels of environmental regulation has come an increasing estrangement between environmental protection and business interests. An uneasy coexistence has evolved into a heated battle pitting the federal government, state governments, business, and the environmental community against each other in a contest over control and use of the nation's natural resources. The eventual outcome of this conflict will have a substantial affect on generations of future Americans as well as on the global community at large.

Perhaps nowhere has this controversy been more visible than in the building industry. Land use restrictions, impact fees, mitigation and other compliance costs, and delays precipitated by permitting procedures are given as the means by which environmental protection has stymied builders and adversely affected their livelihoods (Branconi, 1996). Housing researchers, as well, maintain that financial burdens imposed by environmental regulations have played a large part in driving the cost of new homes beyond what can be borne by most first-time buyers, thereby helping to create an affordability crisis (Olenik and Cheng, 1994; Meeks, 1992).

This paper reviews some perceptions about housing affordability, environmental protection, and the public's attitude toward the environment in hopes of contributing to the development of a new, more realistic perspective on what has become an increasingly muddled situation.

## Homeownership Rates, Prices, and Affordability

A decline in homeownership during the 1980's, viewed against a backdrop of housing prices that had been steadily increasing since the early 1960's, has been interpreted by many housing analysts as an indication of a housing affordability "crisis." Due to the amount of attention given to this issue, a widespread perception has developed that a serious, generalized affordability problem was beleaguering the nation's housing markets. To many, the cause of this alleged affordability problem seemed clear: housing prices had finally risen to the point that many American households simply could not afford to purchase.

A review of the literature, however, indicates a division of opinion as to the merits of this conclusion. Some see the existence of a crisis in affordability as hinging on differing interpretations of home ownership trends. While many believe the decline in homeownership is an indication of an affordability problem, others view it as being more the result of changing demographics (Koebel and Zappettini, 1993).

While earlier generations tended to marry and begin families in their twenties, recent years have seen these events postponed or forsaken altogether. The number of single-parent families has risen sharply. Other less traditional types of households, such as those composed of non-relatives and individuals who simply choose to live alone, have also increased. These fundamental societal changes are seen as having had a profound effect on home ownership rates (Koebel and Zappettini, 1993).

This demographic view of lower home ownership rates is countered by other theories such as that of Linneman and Megbolugbe (1992) which seek to explain the phenomenon in economic terms. In defining the scope and causation of the so-called affordability crisis, these authors present three points that offer a very useful lens for examining this issue.

First, Linneman and Megbolugbe (1992) reject the notion that an affordability crisis has ever existed for affluent young households. The decline in home ownership within this segment of housing markets is attributed to demographic changes. Secondly, they admit that low-income households have experienced affordability problems, but these are seen as being due to income inadequacy, incomes too low to keep up with concurrent increases in housing prices (which are seen as having been caused mainly by a substantial increase in the quality of housing stock). Affordability for low-income families is a long-term problem, one which, although undoubtedly exacerbated by rising home prices and economic upheavals in the 1970's and 80's, was not caused by them.

Thirdly, Linneman and Megbolugbe (1992) identify the real focus of affordability concerns as being on the middle class, which in the 1970's began to confront decreasing housing affordability for the first time. Indeed, it seems to have only been when this group began experiencing problems that the notion of a crisis surfaced and the issue of affordability moved to the forefront in housing policy circles. This phenomenon attracted the attention of housing researchers (and the housing industry) because the middle class, unlike low-income households, was a group that had not previously experienced such problems (Linneman and Megbolugbe, 1992). This is seen as the crux of the affordability crisis.

Linneman and Megbolugbe's (1992) interpretation of the problem therefore, is that middle-class households in some parts of the country, those households having low levels of job skills and education, began to experience affordability problems not because of the mere fact that housing prices had risen, but because their incomes became stagnant or in many cases declined.

The degree of financial security such households had previously enjoyed was based largely on income from relatively well paying manufacturing jobs. This changed when the global economy took hold and manufacturing jobs in the United States went to developing countries, being largely replaced by lower-paying jobs in the service industry. Wage earners in affected households were not able to find jobs in the service industry paying wages comparable to those offered by the lost manufacturing jobs. The resulting income disparity precipitated the decline in home ownership (Linneman and Megbolugbe, 1992).

Yet another economic interpretation of falling home ownership rates is posited by Mayer and Englehardt (1996). While they admit the role of such factors as increasing real house prices, changing demographics, declining incomes, and rising interest rates result in the decline of home ownership, these authors contend that these factors alone cannot explain the phenomenon. Statistics showing an increased reliance by first-time homebuyers on financial gifts to make down payments, along with longer periods of time needed to accumulate down payments, are presented to show that, even when income may be adequate to make mortgage payments, down payments may present a substantial obstacle for many potential home buyers (Mayer and Englehardt, 1996).

Mayer and Englehardt (1996) do not emphasize the relationship between declining home ownership rates and the simple fact that homes were more expensive relative to the past. The focus here is on a specific demand-side problem: the difficulty in providing a down payment. This in turn is seen as due to the well-known propensity of Americans not to save money, as well as to restraints on saving represented by increasing credit card and other consumer debt.

As evidenced by even this truncated review of the literature, there is little agreement that the decline in home ownership experienced in the 1980's constituted a "crisis" or that is was due simply to house prices that had risen so sharply as to preclude purchase. The varying interpretations present in the literature, if merged, produce a more likely view in which changing lifestyles and tastes, along with income and related demand-side variables such as higher levels of consumer debt and low personal savings rates, controlled homeownership rates more than house price increases.

The widespread, lopsided perception that buyers were simply priced out of the market still exists in spite of evidence supporting a more complete and plausible explanation for decreased home ownership. Given this, solutions for bolstering ownership rates tended to focus on specific factors seen as contributing to escalating house prices, one of these factors being the cost of environmental protection.

### House Price Increases and Environmental Protection

To the extent that house prices have increased, what role might environmental protection have played? Downs (1992) states outright that federal environmental regulations, specifically the Endangered Species Act and wetlands regulations, are not significant contributors to the increase in housing costs.

Branconi (1996) examines the escalation of house prices between 1963 and 1993 and determines that environmental regulations may have played a role in the increase. He feels that factors which should have positively affected housing affordability by moderating further price increases were offset, at least partially, by an increase in costs associated with environmental protection.

In rebuttal to Branconi (1996) Evans (1996) argues that there is no direct connection between increased environmental regulation and house price increases. In support of this thesis, he points out that during the first one-third of the period studied, environmental regulations affecting housing were all but nonexistent and yet house prices rose. Given this, the author concludes that the observed rise in prices cannot be explained by environmental protection costs. This argument is bolstered by the fact that the home ownership rate in the U.S. is currently at a record high of 66.8 percent (Seiders, 1998), and that this has occurred without a significant rollback in environmental regulations.

Evans (1996) also sees as significant the disparity between regional house price activity and environmental progressivity. This too, is believed to indicate that increasing environmental regulation and escalating house prices are largely unrelated. As an example, real house prices in the environmentally progressive Northeastern part of the United States dropped substantially between 1973 and 1983 in spite of the fact that a wide range of new environmental regulations were being implemented during the period. Conversely, in the South and West (excluding the West Coast), which are less environmentally progressive, real house prices rose during the same period. Evans (1996) believes the opposite result would be expected if the cost of environmental protection did exert substantial upward pressure on house prices.

While not denying the possibility that environmental regulations have contributed to house price increases over the last thirty years, Evans (1996) believes that the connection between implementation of environmental regulations and price increases, when compared to other forces at work, is minuscule at best.

Meyer (1998) makes the environmental protection/development controversy more specific by examining one of the most controversial federal environmental programs, the Endangered Species Act (ESA) and its affect on the building industry. Meyer (1998) analyzed economic impacts of (ESA) from two perspectives. First, he examined potential relationships between listings of the spotted owl in the Pacific Northwest of the United States and prices for lumber and single family homes. He then observed rates of growth in state real estate markets, after controlling for a number of variables, and compared this growth with increases in listings of protected species.

In the first part of his analysis, Meyer (1998) plotted Douglas Fir production against housing starts. The latter variable historically follows a cyclical pattern (REF), as was illustrated in this study for the period 1970-1995, when Douglas Fir production cycles matched those of housing starts. The author correctly concluded that while there may have been some impact of the spotted owl listing on Douglas Fir production, that impact is minuscule by comparison with the long-standing relationship between that production and housing starts. He went further in this stage of analysis and compared median prices of new homes with Douglas Fir prices. Again he presented convincing evidence that no relationship exists, and that home price increases are more likely related to size and amenity increases in new homes.

In the second stage of his analysis, Meyer (1998) regressed each state's growth in its real estate industry against appropriate industry indicators. After regressing numbers of listed endangered species against those same variables, he plotted the residuals from both sets of equations to demonstrate increased real estate activity with increases in endangered species listing. While this result may initially appear confusing, Meyer's (1998) conclusion is that in robust real estate markets, increased encroachment on wildlife habitats is expected but markets adjust and are not adversely affected. This is a key finding from this study--markets adjust.

Linneman and Megbolugbe (1992) consider that housing price increases have been due mainly to significant increases in the quality of housing stock. These authors also point to inflation in the 1970's and 1980's and the increasingly speculative nature of homeownership in response to inflation, as contributing factors. Koebel and Zappattini (1993) too, identify the increasing quality of houses and their amenity levels as a factor in price increases. Evans (1996) identifies a number of factors as being responsible for increased house prices including demand and demographics. Other contributing factors he cites are increases in house size and quality, rising interest rates, and general price inflation.

Seiders (1998), citing the results of a survey of builders, points to subdivision controls as being most responsible for unnecessarily increasing housing costs. Echoing this,

Downs (1992) identifies local zoning regulations as the greatest regulatory barrier to the development of less expensive housing.

An important factor which must underscore any debate on this issue is that systematic studies of relationships between environmental protection efforts and house prices are scant, and that it is extremely difficult to accurately quantify the effect of a given regulation or regulatory program on a specific housing development (Suchman, 1996a; Branconi, 1996; Engel, Stromberg, and Turner, 1996). In light of this uncertainty, it is puzzling how many individuals and organizations have been able to so confidently make the sweeping generalization that environmental regulations have had profoundly negative effects on housing affordability (Suchman, 1996b; Olenik, 1994). Clear, specific, and reliable scientific data supporting this conclusion simply do not exist.

**Public Support for Environmental Protection**

Substantial increases in the membership of environmental organizations over the last twenty years indicate a widespread concern for the environment. Results from a number of surveys show that the American public is overwhelmingly in favor of environmental protection (Dunlap, 1992). Such surveys indicate that many in fact, feel the government should be spending more on protecting the environment, and substantial numbers of survey respondents indicated a willingness to pay more for products and services that are produced and provided in more environmentally sensitive ways (Dunlap, 1992). Surprisingly large numbers of those surveyed voiced the opinion that they would be willing to see economic growth sacrificed to protect the environment, and that environmental improvements must be pursued regardless of the cost (Dunlap, 1992).

Dunlap (1992) interprets these data and others as strongly suggesting that public concern for the environment is more solid today than in 1970, that environmental protection has become a consensual issue with overwhelming public support, and that its only opposition comes from a small but vocal minority.

**Analysis**

To investigate issues related to housing development and environmental protection and to better understand perspectives of those directly involved with these issues, the focus group technique was chosen as a means of data collection. This is an appropriate method for obtaining qualitative and quantitative information about a complex topic and is useful for identifying specific areas for further research.

The use of focus groups has been defined as a style of interviewing small groups whose participants provide information about complex topics from a variety of perspectives (Berg, 1998). Moderators solicit opinions through a series of open-ended questions that encourage the expression of individual opinions and interaction among participants. Sessions are typically tape recorded, transcribed, and analyzed through research methods such as content analysis (Tesch, 1995). Findings can be useful for observing and identifying trends, patterns, themes and commonalities.

As a data-collection technique, the focus group has been utilized since the beginning of World War II, when the effectiveness of radio programs on troop morale was studied by military psychologists (Berg, 1998). While marketing researchers have long relied on the methodology since that time, widespread use of the technique by social scientists did not occur until the 1980s. In conjunction with qualitative analytical tools, focus groups have been used extensively over the past decade to investigate human perceptions of numerous issues (Shelton and Atiles, 1995).

Shelton and Atiles (1995) discussed issues related to findings from qualitative research and noted that these are significant to the extent that they are valid. Such validity is attained when there is agreement between a study's intentions and its outcomes. This is best achieved through unobtrusive data collection techniques and precautions against the introduction of a researcher's biases or preexisting theories.

To investigate various points of view on the numerous issues that affect housing affordability and environmental protection, two, two-hour focus groups were conducted in the Fall of 1997—one in Seattle, Washington to represent the West Coast, and one in Gainesville, Florida to represent the Southern half of the Eastern Seaboard. The focus group participants included developers, environmental regulators, affordable housing advocates, environmental advocates, Congressional staffers, students of construction management, and faculty in academic programs of construction management. The specific composition of each group is listed in Table 1.

Questions posed to each focus group elicited comments about the loss of species, housing affordability, equity, property rights, regulatory burdens, and other issues. In both groups conversations covered issues many participants had direct experiences with. For example, in Gainesville the university researcher discussed recent findings about the rate at which endangered species are predicted to be lost; the developer shared his experiences with environmental regulators and endangered species; and the environmental regulator talked about his frustrations with the process through which species become listed as endangered. A consensus that emerged in both sessions, however, was that this type of discussion, with various interests represented, was useful for gaining an understanding of alternative views on these issues.

**TABLE 1. Composition of the Focus Groups**

| Seattle | Gainesville |
|---|---|
| Moderators (2) | Moderators (2) |
| Student | Student |
| Congressional Staffer | University Researcher |
| Builder/Developer | Community College Faculty |
| National Audubon Society Director | U.S. Fish & Wildlife Service Regulator |
| College Professor | Affordable Housing Center Director |
| | Developer |
| | Home Builders Association Director |

Transcripts of the discussions were examined through content analysis software (Ethnograph). Key categories were coded which allowed for identification of passages in which common themes emerged. The key categories, frequencies of their being mentioned during the discussions, and rankings are presented in Table 2.

**Table 2. Frequencies and Rankings of Key Categories**

| Categories | Seattle | Gainesville |
|---|---|---|
| Affordability | 10 (6) | 18 (2) |
| Balance | 29 (2) | 8 (6) |
| Confusing Regulations | 8 (7) | 8 (6) |
| Education | 6 (9) | 11 (5) |
| Environmental | 32 (1) | 18 (2) |
| Equity | 12 (4) | 12 (4) |
| Excessive Regulations | 6 (9) | 20 (1) |
| Low Income | 6 (9) | 4 (8) |
| Needs | 12 (4) | 2 (10) |
| Property | 7 (8) | 5 (7) |
| Public | 11 (5) | 5 (7) |
| Research | 0 (10) | 5 (7) |
| Species | 11 (5) | 5 (7) |
| Sustainability | 11 (5) | 16 (3) |
| Wetlands | 14 (3) | 3 (9) |

The frequencies in Table 2 refer to occurrence rates of concepts that can be categorized by the listed terms, whether the terms were explicitly stated or not. Numbers in parentheses indicate how many times the issue was mentioned during the focus group. Note that in the Seattle group, Environmental issues ranked first as the most frequently mentioned issue, while Excessive Regulations ranked first in the Gainesville group. Affordability tied for second place in the Gainesville group and ranked sixth in the Seattle group.

Following are selected quotes from the discussions that provide a sampling of perspectives on the issues covered. The first quote is from the Seattle group and was coded in the Balance Category:

> "... You have to build what the market wants. You have to be careful that you can do it under the government's rules and regulations. But ... the developer who resists the government tends to have more problems than the developer who does not. And the developer who resists and has more problems with the government increases his costs a fair amount because he is going to spend his time in court. ... I think you can make a living and still follow regulations. The important thing is to understand up-front what they are and plan accordingly."
>
> Managing partner of a large building firm.

An important point in the preceding quote is "understanding up-front." This theme emerged later in this session under the Equity Category:

> "...As a developer you ... analyze that piece of ground and make a decision and purchase based on the rules and regulations in place at the time. Wetlands rules came into play in the mid-80s, roughly. ... The rules and regulations on wetlands changed substantially, even from the time the wetlands rules went into place. Should those landowners be held accountable for a major change in rules and regulations to benefit the public in general--not benefit the developer?... The landowner is stuck with a social cost."
>
> Managing partner of a large building firm.

At several points in both sessions, equitable distribution of the social cost of species or wetlands protection was discussed. During the Gainesville discussion, an unintended consequence of the Endangered Species Act was mentioned:

> "Unfortunately, what I see happening is people using the federal endangered species act as a growth management issue, as a local land use issue. Instead of going to the local governments, going to the state government, going to the local communities, and saying, ... 'Do we care about this issue? And how can we plan with it? How can we get the quality of life issues or the sustainability issues or the economic issues integrated into land use for city use?' As opposed to what we see as the old model, or what people see as

> the old model--which is whatever goes. And there are some people who say , 'I can't really do anything I ... want to do to my property...' I think that is where planning comes into play."
>
> Federal environmental regulator.

Issues related to planning were brought up at many points in both focus groups and were coded in categories that included Environment, Need, Affordability, and others. Sprawl, transportation problems, and inner city decay, are mentioned in the following quote from the Gainesville group:

> "There is a limit to how far cities can grow out before the whole idea collapses. It is starting to reach a point where people are miserable. They drive an hour back and forth to work because they are pushed so far out that (the) inner circle starts collapsing. People start forming the second circle. Of course, the second circles have already started forming, so now they are forming this third circle. ... It can only go so far. I think it would be really great to start concentrating on and invigorating the interior of the cities. Because we have already established ourselves there. ... You would not be going on pristine land or virgin land."
>
> Student of construction management.

The fact that affordability was not the most frequent category in either discussion suggests that focus group participants were more concerned with other aspects of environmental regulations, including Excessive and Confusing Regulations, Balance, Environmental issues, and Wetlands, among others. A surprising amount of agreement was seen in points made by the developers, environmental advocates, environmental regulators, and academics. Property rights were seen as essential, with the main problems viewed as lost property rights without compensation when laws change or species-related restrictions are placed on land after a purchase has been made. A point made in both focus groups was that confusing layers of regulations should be made easier to understand through more coordination among federal, state, and local agencies. The faculty and students of construction management expressed much interest in the issues discussed as well as concern that they are not currently integrated into programs of construction management.

## Conclusions and Implications

Several important points emerge from the literature review and analysis. There are a variety of perspectives as to the extent and reality of a housing affordability crisis. Strong evidence points to a conclusion that what has been perceived as a crisis in affordability was more likely a reflection of demographic trends. The decline in home ownership rates was more accurately explained by changes in tastes and lifestyles and not necessarily economic hardship. Stagnant incomes due to economic restructuring, difficulties in amassing down payments because of neglected savings, and higher consumer debt loads led to the inability of many to purchase homes, the prices of which had indeed risen, but mainly because of substantial increases in size, quality, and amenities.

Examining the literature also makes it quite clear that sufficient data do not exists to draw definitive conclusions regarding the negative impacts of environmental regulations on housing affordability. Arguments that such regulations result in higher housing costs and that they play a significant role in preventing the development of affordable housing lack credibility. And the analysis demonstrated that when the topic of environmental regulations is discussed in focused interviews, housing affordability is not a primary concern. Finally, the state of public opinion on environmental issues indicates strong support among the American public for environmental protection efforts.

This paper has not sought to give an authoritative answer to the question of environmental regulation and affordable housing, but to show that no such answer exists because of insufficient research. The only clear conclusion that can be reached regarding this is that claims of environmental regulation having been a substantial contributor to a housing affordability crisis can be legitimately questioned from a number of perspectives.

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# Building a Balance: Housing Affordability,

Joseph Laquatra, David Kay, Patricia B. Pollak, Nelson Bills, Michael Hattery

**Executive Summary**
Using focus groups, survey, GIS projections and reviewing existing land-use tools in New York State, **Building a Balance** explores opinions about, and options for, Smart Growth in New York. One of the greatest challenges facing the planners, politicians, and promoters who seek to implement a Smart Growth vision is to devise strategies, policies, and designs that can effectively shift the balance of preference towards higher density living in already settled areas. The **Building a Balance** project demonstrates that open discussions among groups that have competing interests regarding land-use and community development are essential to find the common ground that unites them.

**Introduction**

Rates of population growth and housing development across the United States are creating pressures on communities to provide adequate infrastructure services for a growing population. Although the United States experienced a population increase of more than thirteen percent between 1990 and 2000, in New York State that figure was only five-and-a-half percent. While population density in some areas of the state remains stable and in some areas is actually decreasing, other areas are facing increases in population density that result in rapid community changes with negative impacts associated with sprawl. Even in parts of the state with little or no overall growth, sprawl takes the form of decline in central cities and older suburbs at the same time that new construction on undeveloped sites increases. These changes are forcing communities to think about planning issues in different ways. Increasingly, town boards must approach growth decisions with information about loss of open spaces and farmland, impacts on the quality of life, and the range of economic issues associated with development.

In New York State, significant authority to regulate land use has been delegated by the legislature to the state's cities, towns, and villages. Municipal authority to enact zoning law, the most powerful land use tool, is included in the zoning and planning enabling acts of town, village and general city law. More generally, **Home Rule** or **Home Rule Authority** gives local governments expansive powers to adopt laws that relate to their local property, affairs and government. This authority explicitly includes a broad set of laws that apply to "the government, protection, order, conduct, safety, health and well-being of persons or property therein."

Typically, local officials review and approve a variety of isolated development proposals. The specific proposals come in all sizes and focus on housing units, commercial properties and industrial facilities. Generally these proposals must be reviewed without detailed knowledge of the public service costs and revenue benefits associated with them. This raises questions about actual service impacts of various kinds of development, typical revenue impacts of development, related multiplier effects on the local economy, and the associated tax impacts of these multiplier effects.

Moreover, local officials are regularly asked to help make development happen. Help may involve regulatory exceptions, loan guarantees, provision of infrastructure costs, and reduced tax payments. Local governments, particularly small and rural ones, often don't have the numbers or a way of totaling up the quantitative and qualitative impacts to make a solid decision they feel comfortable with. For most local governments the big projects are the exception. A particular board member may see only one or two big projects during his or her tenure on the board of a smaller community, but that project may have long-term impacts on the community. Having good, timely information and a framework to evaluate the impacts and to access needed professional expertise is essential and crucial, especially for small communities to make good decisions.

Smart Growth and similar--if loosely defined--concepts are beginning to capture the public's imagination. Although there is no single consensus definition, a core concept of Smart Growth is that public policies should channel growth and development toward areas that are already under development as much as possible. Policies should aim to encourage high-density, mixed-use designs instead of low-density development, while reducing growth pressures on agricultural lands and open or undeveloped spaces. These policies avoid factors that characterize what is commonly referred to as sprawl: a low-density floor-to-area ratio; unlimited outward extension; "leapfrog" development; single-use and single-story buildings; and car-dependent design. Sprawl typically occurs on the outskirts of cities or in rural areas between urban centers.

**Project Overview**

***Building a Balance: Housing Affordability, Environmental Protection, and Smart Land Use Decisions*** is the title of a research project funded by the U.S Department of Agriculture through the Agricultural Experiment Station and Community and Rural Development Institute at Cornell University. The goal of this project was to examine policies that focus on land use patterns, as well as mechanisms for preserving open space and achieving goals related to environmental protection and housing affordability. This goal was achieved by conducting a series of focus groups in four New York towns that are facing distinctly local development issues: Warwick, Bergen, Clarence, and Ballston Spa.

The focus groups were organized to include developers, county planning officials, town supervisors, mayors, environmental advocates and regulators, affordable housing advocates, farmers, and representatives of citizen coalitions. The moderators solicited opinions on various topics related to growth issues.

Divergences centered on individual property rights versus community goals. Developers felt they were responding to a market demand for single family dwellings on large parcels of land. Planners saw implications of rapid supply side responses that affect community infrastructure and transportation patterns. Owners of properties in existing developments had concerns related to increased property taxes. Both owners and renters in these communities viewed the development of farmland and other open spaces as losses of vital community assets. At the same time, owners of these farms and undeveloped lands felt the economic hardship of maintaining property that fails to meet its full financial potential.

Some of the above concerns were more pronounced in the Warwick and Bergen focus groups, as these communities are facing development-related pressures because of their proximity to New York City and Rochester, respectively. In both of these focus groups, developers responded enthusiastically to participate in the sessions, as did representatives from the other targeted groups. In the Ballston Spa and Clarence groups, however, developers did not respond to the opportunity to participate; consequently, the sessions focused on long range visions for the communities. The different tones of these focus groups reflected the contrasts in the development climates of the communities.

While there was a divergence of opinion on issues such as mechanisms for creating master plans, the implementation of growth boundaries, and state government intervention, participants from a variety of perspectives expressed support for wider use of existing land-use tools such as Purchase of Development Rights (PDR), conservation easements, and incentive zoning. Most agreed that open discussions of growth, with all sides of the debate represented, allowed for a better understanding of the issues involved.

The focus groups demonstrated that common ground exists among groups that are often perceived to be in conflict with each other. The project has identified processes and tools to guide communities through development decisions in ways that facilitate open discussion without creating polarizing disputes among various interest groups. For example, some participants discussed at length existing land use tools that are under- utilized, including cluster development, conservation easements, and incentive zoning. Reasons for this may include a general lack of awareness of such options among members of local planning boards and competing interests among landowners within communities which work to limit their implementation.

## New Yorkers' Thinking about Sprawl

The project enabled further exploration of community attitudes toward growth and development in a statewide survey. Sponsored by Cornell University in May of 2000, this telephone poll of 901 randomly selected New Yorkers touched on a variety of topics related to population growth and development.

There is much pre-existing evidence to suggest that problems associated with sprawl are both familiar to New Yorkers and disliked. At the same time, in their lifestyle preferences and support for public policy, the survey findings indicated that New Yorkers value low density living, open space, and scenic farmland. The more these amenities are absent or threatened, the more strongly they tend to be valued or supported. Urban dwellers are the most likely to express discontent with their home location. Predictably, the low density environments so widely desired most often turn to sprawl when individuals independently attempt to realize their dreams. Smart Growth is being promoted as a solution to sprawl. So far, it is an unfamiliar term to most state residents, including those living in counties with increasing populations.

Our survey did not directly define and measure support for Smart Growth policies. Such policies typically envision new development that concentrates around existing infrastructure, saving taxes while protecting open space and revitalizing existing population centers. Insofar as Smart Growth or New York's Quality Communities policies support such a vision, they will likely enjoy popular support.

However, New Yorkers in the survey expressed widespread, experience-based antipathy to population growth and density. One of the greatest challenges facing the planners, politicians, and promoters who seek to implement a Smart Growth vision is to devise strategies, policies, and designs that can effectively shift the balance of preference towards higher density living in already settled areas.

## The Geographic Information System Approach

In order to learn how to better inform land use policy debates that are often conducted in the absence of any substantive analysis, we explored modeling local land use and related policy changes using several Geographic Information System (GIS) based approaches. GIS approaches enable easy analysis of mappable or spatial relationships by layering different categories of information into one map. For example, soil types, parcel development, watershed flows and town boundaries could be visually integrated. This might be used in a town to measure the acres of prime farmland within a proposed 50 foot buffer around all streams, or to count the total number of large, undeveloped land parcels on good soils.

In conjunction with several related projects, we implemented two approaches to GIS modeling of farmland protection policies in Erie County, New York. In the first approach, we evaluated a unique proposal to make new development contingent upon the developer helping to protect farm land or open space elsewhere in town. In this variant on several common land use protection tools, a developer would not be granted a permit until s/he had purchased the right to build on some undeveloped farm parcels elsewhere in town, typically at a cost less than the full value of the property. This land would be finally protected as the developer would be required to donate to the town the right to any future development of the land.

We used GIS to identify parcels in the municipality that were still available for development and those that were already developed or otherwise not suitable for development. In addition, GIS-based parcel characteristics such as soil type and proximity to major roads were used to assign parcels scores relating to their probability of development and their desirability for preservation as farmland. This information was then entered into a prototype simulation model that analyzed the acreages of land that would end up developed versus protected if the maximum amount of development allowed actually came into being. The simulations were repeated under different policy assumptions about the relationship between new development and the requirement for donation of development rights. How, for example, would the results vary with different ways to account for farmland quality, or if the town required more than an acre to be preserved for each acre that was developed?

In the second approach, we collaborated with the American Farmland Trust to work with a group of three Erie County towns interested in farmland and open space protection. In these towns, we again used GIS to identify parcels that possessed desirable characteristics for either protection as farmland or development (e.g., important agricultural vistas, parcel size, proximity to sewer and water infrastructure). Instead of using this information to model patterns of development under different policy options, GIS was used more simply to create an overall farmland protection priority score for each parcel in the region. The resulting map of parcels with low and high scores is now available to help the municipalities identify properties that could be targeted for protection using appropriate, locally approved farmland protection tools.

**What Can Communities Do?**

Communities can grow and avoid sprawl without new legislation at the state level, though available tools to control sprawl are typically underemployed. Zoning and subdivision regulations, for example, can reflect a community's decisions about land resources, types of buildings, infill development, mixed-use and high-density development, and other issues. New developments that locate homes, stores, schools, offices, and public facilities within walking distance of each other will avoid congested roads and streets. Existing land use tools, such as PDR, can keep designated lands for agricultural purposes without denying farmers the economic gain they would realize from selling their property for development.

Issues surrounding development involve complex decisions by town boards; and local governments are assuming prominent roles in the formulation of growth policies for their communities. Town Board members and the general public can facilitate sound development decisions by approaching them in an informed manner that is sensitive to the needs of all parties in the development process.

**What Can We Do In New York?**

New York State is extremely diverse in its economic, geographic, and land use conditions. Many municipalities would welcome development in any form, while others are struggling to control it. Anti-sprawl and related policies have been adopted or debated in many local communities from Long Island to Erie County. As in other states, a broad array of interest groups-ranging from environmental groups to homebuilders' associations-has participated in the debates. At state and local levels, a diverse coalition of these stakeholders has actively jockeyed for position while seeking common ground and policy influence. Most anchor themselves to a core concept: concentrating new development in or near existing developed areas to avoid sprawling haphazardly across a low density landscape.

Nearly 90% of the state's municipalities have planning boards, but less than two-thirds have written comprehensive plans. Some counties have joined together to form regional planning commissions, and many of these are undertaking development projects that are uniquely suited to their localities. Some have created processes for involving businesses, community organizations, and interested citizens in neighborhood planning efforts. Others have focused on specific projects related to land use and economic development.

New York has made use of mechanisms including the 1996 Clean Water/Clean Air Bond Act, the Open Space Conservation Plan, the New York State Environmental Protection Fund, and the Coastal Management Program to provide funds for communities for projects related to water and air quality improvements, open space acquisition, brownfields rehabilitation, and solid waste management.

In 2000 Governor George E. Pataki issued an Executive Order that created the Quality Communities Program. This initiative linked state and local governments in efforts to foster environmentally sensitive growth and development. The Quality Communities Task Force studied state and federal programs that affect community development and conducted community forums about growth issues around the state. The complete report by the Task Force is available at: http://www.state.ny.us/ltgovdoc/cover.html.

The Building a Balance project demonstrated that open discussions among groups that on the surface appear to have competing interests regarding community development are essential to find the common ground that unites them. Communities can define their long range vision and achieve it through existing policies and land use tools. We developed four fact sheets that have been distributed to all town boards in New York State. We hope these fact sheets will serve as a starting point for discussions that will lead communities to a path that will enable them to realize their vision for smart land use decisions. These fact sheets are available on the Building a Balance page at the Community and Economic Development Toolbox: www.cdtoolbox.org

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# The Economics of Environmental Regulation of Housing Development

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Abstract:

Conflicts over protection of biodiversity and other environmental amenities seem to be at their strongest when housing development is at issue. Housing affordability has emerged as a major national policy issue, and is seemingly in conflict with other mandates to protect and enhance environmental quality. Despite this apparent policy conflict, and despite the enormous potential wealth transfers resulting from environmental regulation of land use changes, it is somewhat surprising that there are relatively few papers linking these two problems. The paper reviews some of the issues arising from environmental regulation of housing development, and highlights a number of areas for future research.

## I. Environmental Regulation of Housing Development

Environmental regulation is a significant hurdle in the housing development process, and is a major part of national efforts to protect biodiversity, environmental amenities, and other landscape features such as wetlands. Governments at all levels routinely conduct environmental reviews of proposed projects to ensure that development is compatible with environmental protection or, at least, that economic and environmental objectives are balanced in some fashion. Interestingly, federal environmental agencies have assumed an increasingly important role in oversight of land use changes, an area traditionally reserved for local governments.

This survey reviews the economics of environmental regulation of housing development. For clarity, this analysis focuses on federal regulations, stemming from the Clean Water Act and the Endangered Species Act, intended to conserve wetlands and habitat for endangered species, respectively.

These regulatory programs have come under increasing scrutiny by academic economists and lawyers. Economists have noted that these interventions, like other land-use controls, have the capacity to transfer large amounts of wealth among groups in society. They can also distort local housing markets and result in general equilibrium changes in location choices, housing prices and commute times. Lawyers have focused on the federalism aspects of these two regulatory programs.

In one sense, the conflict between environmental protection and housing development is not surprising since neither the Clean Water Act nor the Endangered Species Act were designed with economic efficiency in mind. In both cases, Congress acted as if the nation's water quality and species conservation problems could be solved without federal land use controls, and both laws were shaped to avoid direct conflict with the autonomy interests of local governments and private landowners (Dukeminer and Krier, 2002). Consequently, federal environmental agencies lack the authority to mandate ambitious levels of land conservation if that would stop most or all development in affected areas. Rather, federal regulation tends to impose the same moderate requirements everywhere regardless of biological effectiveness (Pedersen, 2004).

*Wetlands*

The discharge of material into wetlands is regulated by the Army Corps of Engineers under Section 404 of the Clean Water Act. Federal regulations provide that the Corps must examine the following main issues in its review of proposed projects:

- Does the applicant have no practicable alternative that would avoid impacts to wetlands and has the applicant minimized unavoidable impacts?
- Does the mitigation proposal adequately compensate for any adverse impacts of the project?
- Does the project contribute to significant degradation of the aquatic ecosystem?
- Is the state where the activity is to take place satisfied that the project is consistent with state water quality standards and coastal zone management plans?
- Is the project contrary to the public interest?

The first two issues are handled according to a process called "sequencing" in which the applicant must establish that all practicable steps have been taken to avoid and minimize adverse impacts before the Corps and other agencies will consider the mitigation proposal. Accordingly, the end result of environmental review is often a combination of avoidance and mitigation. Avoidance often leads to a reduction in the overall output of the project (i.e., a reduction in the number of new homes constructed), and mitigation becomes one component of the transaction costs of regulation. Other out-of-pocket costs include the need to hire outside experts such as attorneys and biological consultants to navigate the permitting process, and the need to redesign the project based on the outcome of the review process.

*Endangered Species*

The Endangered Species Act (ESA) can have a profound effect on housing development, particularly in the western United States. The ESA explicitly prohibits "take" of a listed species, and can even limit development when "take" does not occur if the government deems the project to be on essential, if unoccupied, habitat.

Economic analysis has a role in the endangered species regulatory process in the designation of critical habitat. Section 4(b)2 of the Endangered Species Act authorizes the Secretary of the Interior to exclude land from critical habitat if she determines that the benefits of exclusion outweigh the costs. This exercise has created much controversy, mostly around the method used to assess benefits and costs. The recent *New Mexico Cattlegrowers* case has proved important in helping to settle the issue.[1] Plaintiffs in the case challenged the Fish & Wildlife Service's designation of critical habitat for the

[1] New Mexico Cattlegrowers Assn. v. U.S. Fish and Wildlife Service, 248 F.3d 1277 (10th Cir. 2001).

southwestern willow flycatcher arguing, *inter alia*, that the Service's "baseline" approach to measuring the economic impacts of critical habitat designation was an erroneous construction of the ESA. Under this approach, the Service would consider the initial listing of the species to be part of the baseline and thus would not analyze the economic impacts of listing, but only the economic impacts attributable directly to the critical habitat designation. Applying this baseline approach to the critical habitat designation for the flycatcher, the Service relied on its Section 7 regulations to conclude that no economic impacts would have occurred "but for" the critical habitat designation, and that the impacts of critical habitat designation and listing of the flycatcher were co-extensive.

The Tenth Circuit rejected this "baseline" approach, holding that the Service is required to analyze all impacts of critical habitat designation, regardless of whether those impacts are co-extensive with those of listing. The court acknowledged that the ESA "clearly bars economic considerations when the listing determination is being made." However, the court stated, the ESA also plainly requires "some kind of consideration of economic impact" at the critical habitat designation phase. The Service's regulatory "definition of the jeopardy standard as fully encompassing the adverse modification standard renders any purported economic analysis done utilizing the baseline approach virtually meaningless." Thus, the court concluded, the baseline approach failed to give effect to the congressional directive that economic impacts be considered at the time of critical habitat designation and was not in accord with the language or intent of the ESA.

## II. Environmental Regulation and the Development Process: General Observations

The process of real estate development is highly variable and project-dependent. Nonetheless, it can be divided into several phases, bearing in mind that these are only general patterns. These basic steps apply to development of single-family housing, office buildings, shopping centers and other private sector projects that are the subject of this report.

In the planning and initiation phase, the development team is assembled, major hurdles are identified and overall project objectives are assessed. Next, the feasibility of the project is considered through an assessment of market conditions, local and regional governmental objectives, availability and cost of financing, and potential project sites. Typically, land will be optioned by the end of this phase at the latest. The commitment phase of the development process involves land assembly, preparation and negotiation of environmental documents, assembly of materials needed for other regulatory approvals, preparation of documents needed for financing, and finalizing the design of the project. This phase culminates when the developer obtains the needed financing and regulatory approvals. The developer then moves on to construction and operation of the project.

Real estate development is a complex undertaking and economic analysis of the effects of environmental regulation must reflect some basic features of this process. Some of these realities include the following:

- Development is subject to multiple, uncoordinated regulatory processes.
- Federal regulation can be a "signal" that increases the cost of other regulation.
- There are numerous physical constraints on site selection.
- Development is sequential in space and with regard to the regulatory "queue".
- Project delays can be very costly to developers, consumers and others.

- Development process requires sufficient financial and human capital.

Each of these factors in turn will be addressed further and with an emphasis on how they affect economic analysis of environmental regulation.

While the subject of this study is primarily federal environmental regulations, a salient fact about the land development process is that it is the subject of a complex web of federal, state and local regulation. These processes are largely uncoordinated and have differing objectives, but they are interrelated in that the outcome of one permitting process can reverberate through the others. One dimension of this interrelation is that if the outcome of federal regulation is to reduce the size or configuration of a housing project, for example, this modification will require the developer to alter the application to the local agency. Another dimension of this interrelation is that findings from one process can influence decision-making in others.

A consistent observation of the developers who were interviewed as part of this study is that once land is labeled as critical habitat or waters of the United States, all environmental permitting processes become more onerous. An important implication of this finding is that federal environmental regulation can impose significant costs on development even if the project has no federal nexus.

Public decision makers take into account the impact of the regulation on various constituencies, including environmental groups, local businesses, landowners, developers, agency budgets etc. Agencies differ in the weight given to various factors. Federal agencies are less likely to consider non-environmental factors and are less certain in their requirements. Local agencies are more likely to balance economic factors with environmental impacts.

Another aspect of coordination is that land can be subject to multiple environmental regulations. The cumulative effect of environmental regulations is likely to be larger than the sum of individual effects. Unless habitat associations are perfectly correlated across species or targeted amenities, adding regulations increases the amount of land set aside and increases permitting costs.

Any designation at the federal level may affect the treatment at the local level by a "signaling" effect. Regulators operate under uncertainty and may be risk-averse. Any designation that federally-protected amenities are present on a property may raise a flag about negative environmental impacts and lead the local agency to take a more conservative perspective on the development project. The response of local agency to federal regulation may vary depending on local sensitivities to environmental protection and economic development, as well as the extent of knowledge on the part of local agencies and the public. This way of thinking about the signaling effect of environmental regulation leads to some interesting predictions:

- The less informed the local agency is about the local environment, the more likely designation is to increase the difficulty of permitting.
- The more emphasis the locality places on environmental protection versus economic development, the stronger the impact of designation on local approval.
- The higher the actual risk posed by development is, the stronger the impact of federal regulation.
- Designation has an economic cost even on lands with no federal nexus. It may affect the severity of treatment and delay approvals at the local level. The delay effect will be larger in cities and counties with a more limited permitting capacity.

Site selection can occur before or after the developer evaluates local market conditions. This process is often exhaustive since a large number of factors are relevant to the site selection process. In fact, the National Association of Home Builders has developed a list of over 1,000 factors that should be considered before acquiring land for development. Among the factors that make a site suitable for development are the following:

- location and neighborhood
- size and shape
- accessibility and visibility
- environmental conditions
- legal constraints
- utilities
- zoning and regulation

The cumulative effect of these factors is that, while an area may appear to have a large amount of vacant land available for development, in reality there can be little land actually or realistically available for development. Imposition of additional regulation may reduce the amount of land available for development in a region, reduce the regional stock of housing and other goods and create unintended consequences on other resources such as agriculture and local planning processes.

Other factors constrain the development process. "Leapfrog" development is increasingly problematic since local governments often seek to confine development within defined boundaries. Further, non-sequential development requires utilities, roads and other infrastructure to be extended longer distances, thereby increasing project costs.

Thus, land located away from the urban boundary may be, at best, an imperfect substitute for land located on the boundary which is set aside for habitat protection.

Local governments have limited capacity to process permit applications and may consider them in the sequence in which that particular local government would like the area to evolve. Most developers can recall instances in which they were forced to wait long periods, in some cases several years, for a local government to work through its backlog of applications for projects that were closer to the city center.

Delay is another impact of environmental regulation on the housing development process. Sunding and Zilberman (2002) offer some direct evidence on the length of time needed to obtain a discharge permit from the federal government. Based on a nationwide analysis of individual wetland permit applications, they conclude that the average permit takes a total of 788 days to prepare and negotiate. Of this amount, 383 days are required for preparation (that is, from initiation of the process until submission) and 405 days from submission until receipt of a decision from the Corps.[2] Environmental review is often the pacing item in a housing development project, especially since local environmental reviews can be impacted by federal decisions about mitigation and avoidance.

[2] These figures are in contrast to the Corps assertion that it takes only 127 days on average to obtain an individual permit. The discrepancy is largely explained by the "completion game" in which months or years can pass before the Corps deems an application to be complete and therefore ready for review.

Consider the costs of delay on just one component of land development expense such as the cost of acquiring land. The developer typically acquires land for the project in three steps: a "free-look" period, a period in which the developer has locked up the land with an option to purchase, and closing. Developers usually acquire an option to purchase fairly early in the process.

The welfare cost of delay (and of the related uncertainty about permit completion time) can be large. Mayer and Somerville (2000) show that delay can have a significant negative impact on development incentives. Majad and Pindyck (1987), Grenadier (1995) and Bar-Ilan and Strange (1996) also consider the incentive effects of delays in the context of a dynamic optimization framework. While these papers focus on the supply side of the market, it is also important to note that consumers bear significant costs from delay since they lose all consumers surplus during the period of delay (Sunding, Swoboda and Zilberman, 2004).

**Table 1**

**Typical Months Elapsed for a Small Office or Apartment Building**

| | **Stage of Development** | **Area with Few Regulations** | **Area with Many Regulations** |
|---|---|---|---|
| **1.** | Earnest Money Contract Signed | 0 | 0 |
| **2.** | Earnest Money Committed | 1 | 1 |
| **3.** | Market Study | 2 | 2 |
| **4.** | Preliminary Design | 3 | 3 |
| **5.** | Engineering Studies | 6 | 6 |
| **6.** | Approvals[a] | 6 | 24-60[b] |
| **7.** | Financing Commitment | 6 | 24-60 |
| **8.** | Working Drawings and Building Permits | 9 | 27-63[c] |
| **9.** | Land Purchase and Construction Loan Closed[d] | 9 | 27-63 |

[a]Assuming no zoning changes are necessary.
[b]Environmental, political, design review, and other approvals can take two to five years.
[c]Building permits can take six to nine months after working drawings are finalized.
[d]Most sellers require closing on the land sooner than nine months, but the deal should not be finalized until tentative financing commitments and approvals are in place.

*Source:* Urban Land Institute, 1989.

Table 1 shows how the development process can be affected by environmental regulation. In this stylized example prepared by the Urban Land Institute, the developer acquires an option near the start of the development process, only one month after initiation (even before performing a market analysis). The developer must then pay to maintain this option until all regulatory approvals are obtained. In areas like California where land is expensive, delay can significantly increase development costs.

The ultimate decision to assemble land and construct a project is the result of many factors. If environmental regulation requires a redesign of the project or simply delays receipt of needed permits, overall project costs can increase significantly. For example, if environmental regulation reduces the number of allowable units in a project, then the developer may need to redesign the entire project, reconsider the financial analysis, and rework financing.

Beyond increasing development costs, delay can reduce societal benefits from development in other ways. One obvious effect is that delay reduces the present value of development by pushing consumption further into the future. Thus, delay reduces the present value of the developer's return on investment and the final consumer's enjoyment of the product. In extreme cases, delay can lead to bankruptcy if the developer is highly leveraged. Delay may also lead to relocation of key industries away from the region as they search for needed facilities. Delay can also increase the costs of related infrastructure development – cost often borne by cities or counties.

Taken together, these observations imply that the development process may be highly constrained, and environmental regulation to conserve habitat can reduce the stock of housing and increase its market price. To summarize:

- Regulation increases development cost and reduces the size of affected projects.
- Because numerous constraints on development reduce the substitutability of projects, regulation can reduce the size of regional housing stock.
- Environmental regulation can alter the configuration of cities, squeezing development out of some fringe areas, resulting in increased commute costs, sprawl and other problems.
- Development projects can be delayed by environmental regulation, resulting in increased development costs and other effects.

The impacts of habitat protection go well beyond the developer and landowner to include current and prospective homebuyers, commuters, local government and others.

## III. Conservation Benefits and the General Equilibrium Effects of Regulation

Spatial models are widely used in urban economics to explain various characteristics of the urban landscape (see Anas, Arnott and Small, 1998, for a review). These models have been adapted to consider such problems as urban sprawl (Brueckner, 2000 and 2001, Fujita and Kashiwadani, 1989, Mills, 1981). Models of this type have also been extended to consider the provision of open space and environmental amenities (Yang and Fujita, 1983, Lee and Fujita. 1997, Wu and Plantinga, 2003, and Brueckner, Thisse and Zenou, 1999).

By protecting habitat and other local amenities, environmental regulations can increase the demand for housing in a particular location. These benefits should be considered when drawing any conclusions about the size or distribution of the costs and benefits from environmental regulation of housing development. While it is hard to draw general conclusions about the market effects of habitat protection, it is possible to identify alternative scenarios.

It is tempting to consider the benefits of environmental regulation in the same way that one would model the benefits of providing open space or parks. This would be a mistake. Protection of open space usually results from an indigenous planning process that expresses the preferences of local residents. Federal environmental regulation, by contrast, flows from the preferences of the nation as expressed by Congress, and preserves habitat only by overturning the decisions of local governments. Further, by negotiating with individual applicants and requiring changes to a large number of independent projects, the conserved habitat resulting from regulation can be fragmented, isolated and of debatable recreational or aesthetic benefit (if it is accessible at all). There is also a question about proximity to the conserved habitat. The principle of off-site mitigation is well established in both wetlands and endangered species regulation. Thus, the end result of regulation may not be to conserve habitat near the area in question, but many miles away and, thus, be of little direct benefit to those homeowners. While the conserved habitat may be valuable, benefits are separable from costs since they do not affect the regulated housing market. Finally, the quality of conserved habitat may be questionable. Again, wetland regulation provides a good example. Many landscape features that are regulated as waters of the United States are not highly valued by neighbors and, indeed, are sometimes considered nuisances. Such features may include irrigation canals, desert washes, roadside ditches and tire ruts, and erosional features on hillsides. Again, the implication is simply that benefits are separable from costs and need not affect the location choices of households.

These observations suggest that the benefits of regulation are hard to characterize acontextually, and that different possibilities need to be considered. Unlike the case of open space, there is a very real possibility that the land conserved as a result of environmental regulation provides few if any benefits to local residents. Thus, it seems prudent to consider two alternative scenarios regarding benefits: i) The benefits and costs of regulation are separable in that the benefits of regulation do not affect the location choice of households; and ii) conserved habitat is a local public good that benefits homeowners as a declining function of distance to the preserved habitat.

The first scenario can be dealt with through partial equilibrium analysis, which is addressed in the next section on screening analysis. There are some results in the literature that shed light on the general equilibrium effects of environmental regulation in the case where benefits are local public goods and affect housing market choices. In general, environmental regulation can perturb the urban economic equilibrium in two ways. First, it acts as a development tax in that it increases the cost of converting open space into housing. Second, it may provide localized amenities that increase the utility from housing consumption in certain locations.

Measures of the willingness to pay for local environmental amenities are treated in various studies including Acharya and Bennett (2001), Leggett and Bockstael (2000), Mahan, Polasky and Adams (2000), Breffle, Morey and Lodder (1998), Kline and Wichelns (1998) and Palmquist (1992). This research is of variable quality, with most papers suffering from the serious defect that they do not distinguish between the supply-reducing effect of regulation and its benefits, but rather infer that observed price changes result from the creation of local amenities.

The recent paper by Wu and Plantinga (2003) illustrates the kind of general equilibrium effects that can result from habitat conservation in the case where regulation creates local public goods. For example, they show that open space policies should not be viewed as independent of, or even compatible with, growth management goals. Ignoring the cost increasing feature of land conservation, their analysis shows that creating open space will distort the location choices of households since residents prefer to live close to open space and the creation of open space has an extensive margin effect by attracting migrants to the city. They also find that the creation of open space can create leapfrog development, increase the total size of the city, and result in congestion externalities.

Another interesting finding of the Wu and Plantinga paper is that the creation of open space may be highly regressive. In equilibrium, housing is allocated to those who bid the highest price, indicating that households with a relatively flat bid price gradient with respect to the central business district will locate further from the city center. The standard result from the neoclassical model of urban growth is that the distribution of income groups in relation to the central business district depends on the relative magnitudes of the income elasticities of housing demands and marginal travel costs. If income has a larger effect on housing demand than on marginal travel costs, then wealthier households will locate farther from the central business district, as observed in many cities in the United States.

Environmental regulation that creates open space can change the location pattern of different income groups because it changes the spatial distribution of amenities. Wu and Plantiga (2003) consider various forms of open space (ignoring congestion effects) and simulate outcomes. In these simulations, the designation of open space shifts upward the bid price function of all households. However, because the open space is located some distance from the central business district, it tends to benefit high-income households more than low-income households. In all scenarios, creation of open space causes more high-income households to migrate to the city. Moreover, the high-income households locate closer to open space but further from the central business district where they face more favorable tradeoffs between housing and transportation costs.

## IV. Measuring the Cost of Conservation at the Project Level

Partial equilibrium analysis is useful for screening to identify areas of cost-effective conservation. Its data requirements are much more modest than that of general equilibrium analysis. Because it is relatively easy to implement, partial equilibrium analysis is supportive of more efficient implementation of clean water and biodiversity conservation objectives than the current system of untargeted regulation.

There are two basic theories of housing market equilibrium, and both should be considered in the partial equilibrium analysis. The most common approach is to assume that the price of housing reflects the marginal cost of construction and development. In this view, commonly called the neoclassical approach to housing market equilibrium and taught to every graduate student in urban economics, density will adjust to equate the price of land with its marginal value to consumers. This view also holds that developers do not earn excess profits from their activities.

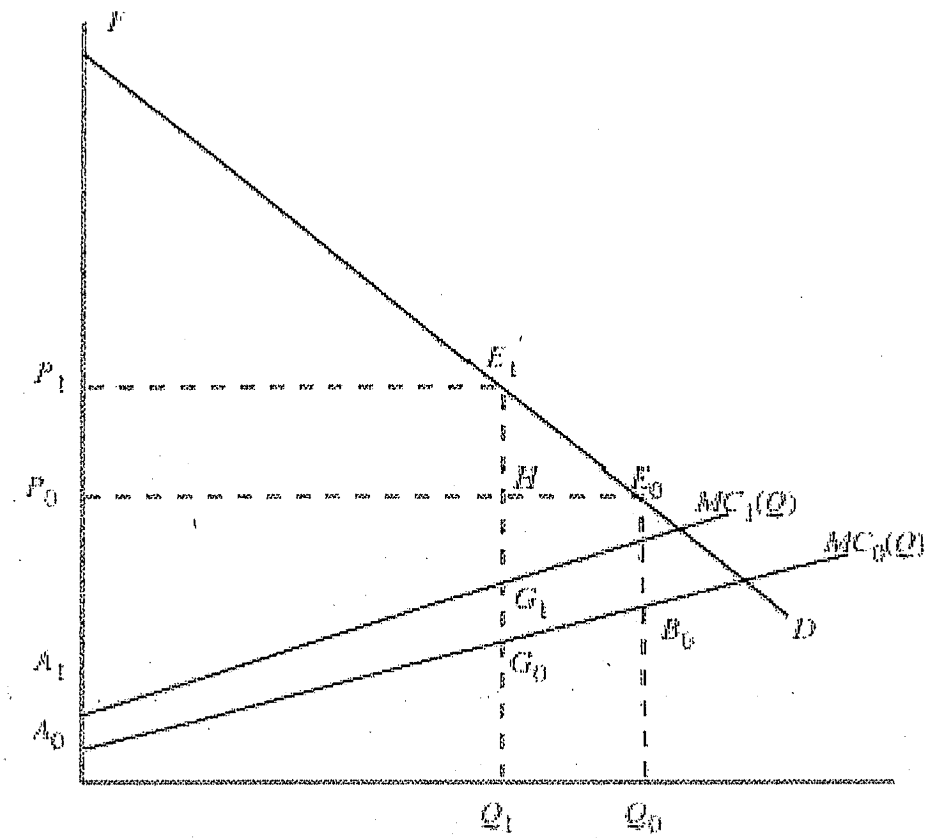
An alternative approach stresses the importance of regulation such a zoning and density controls that limit the supply of housing (Sunding and Swoboda, 2004, Glaeser and Gyorko, 2004). In this approach, the marginal cost of construction and development can be far below the market price of a house since houses are rationed among a number of consumers and their price is bid up accordingly. Thus, in the regulation-focused approach, housing prices reflect scarcity more than the costs of production. In this view, the value of land with a house on it may be far greater than the willingness of consumers to pay for an additional unit of lot size.

This distinction between the neoclassical and regulation-focused explanations of the price of housing is important to the impact of environmental regulation on the housing industry. In markets where housing prices reflect marginal costs, the impact of regulation on costs of construction and development will be of the most importance; the marginal welfare costs of output restrictions are negligible since marginal cost equals marginal utility in the pre-regulation equilibrium. When housing supply is limited and houses are rationed as a result, the supply-reducing effect of environmental regulation takes on major significance. By further restricting supply, environmental regulation imposes costs on consumers and results in losses to landowners and developers undertaking projects on conserved land.

Figure 1 shows the partial equilibrium impact of environmental regulation on the housing market. Let the demand for new housing in a region be given by $P = D(Q)$. Benefits are treated as separable in this case, and the analysis focuses on cost in an effort to screen out areas of high impact. The pre-regulation quantity of development occurs at $Q_0$, reflecting the fact that land at the project location earns some quasi-rents.

**Figure 1**

**Partial Equilibrium Analysis:**
**Impact of Regulation on the Local Housing Market**




Environmental regulation increases the marginal cost of homebuilding in that the developer must expend resources to get through the permitting process, redesign the project if necessary, and perform off-site mitigation. The post-regulation marginal cost is denoted by $MC_1$.

The second effect of environmental regulation is to reduce the output of the project in an attempt to minimize on-site impacts. This effect is captured in the reduction in project output from $Q_0$ to its post-regulation level, $Q_1$. An important consequence of the reduction in supply is that the price of new housing increases from $P_0$ to $P_1$. This change in price transfers wealth from consumers to developers and landowners.

The third main effect of environmental regulation is to delay completion of the project. The loss from delay is potentially quite large, and has been generally overlooked in the economic literature on regulation and permitting. The surplus concepts in Figure 1 are net present values since housing is a durable good. Thus, the costs of delay involve the total amount of surplus lost from the failure to build during the period of delay, the length of this period, and the rate of interest. The cost of a one-period delay in completing the project is essentially the area of total surplus multiplied by the rate of interest.

An example will help to illustrate data requirements, how to calculate welfare losses, and the potential range of welfare costs. Consider a 1,000-unit housing project proposed on a 250-acre parcel, implying a gross density of 4 units to the acre (typical for suburban Southern California). Suppose that the market price of the new homes is $250,000 and that the constant marginal cost of development and construction (exclusive of land assembly costs) is $200,000 per housing unit.

Environmental regulation of the proposed land use change impacts the development in three ways: The cost of development is increased by $6,000 per unit, the number of homes is scaled back to 900, and completion of the project is delayed by one year. Under the assumption of a unitary demand elasticity, application of the impact framework shows that the price of housing rises to $275,000. The total welfare loss is $28.5 million, over half of which results from delay.

An interesting extension of this example is to consider environmental regulation's implicit cost of conservation. If the end result of the permitting process is to prohibit development on one-tenth of the total acreage of the project, then the $28.5 million dollar welfare loss should be divided by the 25 acres preserved by regulation. Viewed this way, the cost of conservation exceeds $1 million per acre.

## V. Conclusions

The topic of environmental regulation of housing developments draws on several themes in economics, in particular urban economics and environmental economics. Despite the large number of papers on urban growth processes and on the costs and benefits of environmental protection, it is somewhat surprising that there are so few papers on the impact of environmental regulation on housing development. Given the potential for large wealth transfers and amenity creation, this seems to be a major area of opportunity for economists, policy analysts and others who study processes of urban growth and development.

Housing development is subject to an array of overlapping regulations. Thus, the textbook neoclassical model of urban growth may be of limited relevance to the task of measuring the costs and benefits of environmental regulation. Rather, what is needed is a detailed model of the housing development process, and a more complete understanding of how developers interact with regulators and how the regulatory process alters the sequence and timing of development activities. Further, environmental regulation of land use changes is conducted by numerous levels of government, raising interesting questions about the possibility for interaction among regulatory agencies and additional problems caused by a lack of coordination.

Another area in need of further research is the question of measuring the benefits from environmental regulation of land use changes. Some environmental economists have a tendency to equate stopping development with provision of meaningful public goods. While there have been some attempts to measure the value of preserving open space, it is hard to draw general conclusions about the benefits of protecting habitat on the margins of urban areas. Further, most economists attempting to measure the benefits of protecting environmental amenities such as wetland and open space fail to adequately account for the supply-reducing effects of environmental regulation that may, by themselves, account for observed price differences.

While most of the discussion in this paper has been couched in terms of partial equilibrium, protection of habitat may have interesting general equilibrium effects on urban form. For example, if some land is placed off-limit to development, the market may respond by encouraging development in more remote areas. Regulation may even result in leapfrog development that strains public infrastructure. Thus, the benefits of environmental regulation may be best studied in terms of competing risks, as is common with other kinds of regulation.

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NATIONAL ASSOCIATION OF HOME BUILDERS

## BUILDING A BALANCE: BIBLIOGRAPHY

Normal View

This fact sheet has been created in the form of an annotated select bibliography of literature addressing the issues of housing affordability and environmental regulation. The particular emphasis is on connections between the two.

No attempt has been made to create an exhaustive record of the literature in these fields. Instead of presenting a large number of sources addressing a limited variety of topics, it was thought more useful to present a smaller number of sources which present the broadest spectrum possible of issues relating to the subjects in question.

You will find here monographs and articles that view issues of importance from both scholarly and popular perspectives. Included are works which discuss theory and some of a more practical nature. This approach is designed to provide an understanding of basic concepts in addition to information of more immediate importance and usefulness.

The sources listed in this bibliography have also been selected to present various points of view on the issues represented. By offering differing perspectives, it is hoped that the information contained in these resources will lead to more informed, balanced dialogue which will in turn result in a better understanding of the shared challenges facing the building industry and environmental preservation.

This bibliography was compiled by Greg Potter, of the Home Builders Institute, and Professor Joseph Laquatra, of Cornell University.

***Suggestions for Using the Bibliography***

Schedule a debate or colloquium to discuss a topic drawn from the readings. Divide students into teams or panels with one team arguing the "pro" position and the other the "con" position of the issue selected. Have the teams prepare arguments using readings from the bibliography.

Assign a reading or readings from the bibliography (or have students choose them) to serve as the basis of a written report or an oral presentation.

Have students choose a reading from the list and do further research on the topic of that reading. The result could be a written report, an oral presentation, or a bibliography of their own listing sources not included in this bibliography which relate to the topic of original reading.

Have students choose a book or article from the readings that presents a particular view of a given issue, and then choose another source from the list that presents the opposite view of the same issue. After the student has studied the two sources thoroughly, have him or her give an oral or written report on their findings and tell which interpretation of the issue seems most convincing and why.

Assign a representative sampling of sources from the bibliography for students to read (be sure the sampling contains readings about a variety of issues) then have the class discuss the various issues with an emphasis on ranking them based on their potential impact on the building industry.

Have students study readings from the bibliography dealing with a specific piece of environmental legislation (such as the wetlands provisions of the Clean Water Act) or a collateral issue (such as the private property rights implications of the Endangered Species Act). Once the student has chosen a statute or issue, have him or her search newspaper and magazine indexes to find a case where the legislation or related issue caused a controversy and report on the findings.

**Access EPA.** (Washington, D.C.: United States Environmental Protection Agency, 1995). Most current edition of directory of EPA and other public-sector environmental resources. Contains the history and organization of EPA and contact information for personnel in the Washington, D.C. headquarters and regional offices: lists EPA hotlines and clearinghouses, publications, and EPA databases accessible by the public.

**Adler, Robert,** "The Clean Water Act: Has It Worked?" Environmental Protection Agency Journal 1, no. 20 (1994): 10-15. Argues that although the Clean Water Act has resulted in some improvements in the nation's waters, there is still much to be done in meeting even the Act's most basic goals.

**Baldauf, Craig Robert,** "Searching For A Place to Call Home: Courts, Congress, and Common Killers Conspire to Drive Endangered Species Into Extinction," Wake Forest Law Review 30 (1995): 847-887. Examines the Endangered Species Act with emphasis on how it might be improved to make it more equitable and effective. Stresses the continued need for protection of biodiversity.

**Baur, Donald C., and Karen L. Donovan,** "The 'No Surprises Policy:' Contracts 101 Meets the Endangered Species Act," Environmental Law 27, no. 3 (1997): 767-790. Explains the rationale behind the "no surprises" policy of the Endangered Species Act and how it is essential to the continued effectiveness of the Act by making it more flexible and equitable.

**Bingham, Gail, and others, ed.** Issues In Wetlands Protection: Background Papers Prepared for the National Wetlands Policy Forum. Washington, D.C.: Washington Conservation Foundation, 1990. Offers a variety of perspectives on wetlands protection and management. Papers examine the need for more information about wetlands, the importance of a focus on wetlands hydrology as well as on land issues, the need for both public and private sectors to share the burdens of wetlands conservation, and the effectiveness of regulatory efforts to conserve wetlands.

**Bormann, F. Herbert, and Stephen R. Kellert, ed.** Ecology, Economics, Ethics: The Broken Circle. New Haven: Yale University Press, 1991. Examines relationships between ecology, economics, and ethics. Discusses the need to reintegrate the three in order to create successful and practical long-term solutions to preserving the environment. The chapter on environmental ethics is particularly thought-provoking.

**Bossleman, Fred, David Callies, and John Banta.** The Taking Issue: A Study of the Constitutional Limits of Government Authority to Regulate Privately-Owned Land Without Paying Compensation to the Owner. Washington, D.C.: Council On Environmental Quality, 1973. This book is an excellent study of the political and legal history of Constitutional powers affecting land and how the courts have interpreted those powers. Takes a look at what future options might be open for legislative and judicial action in property rights cases.

**Bowles, Ian, David Downes, and Marianne Guerin-McManus,** "Economic Incentives and Legal Tools for Private Sector Conservation," Duke Environmental Law & Policy Forum 8, no. 2 (1998): 209-243. Discusses a number of economic incentives (such as conservation easements, land exchanges, and tax incentives) which may be used to encourage environmentally responsible use of resources.

**Branconi, Frank,** "Environmental Regulation and Housing Affordability," Cityscape: A Journal of Policy Development and Research 1, no. 2 (1996): 81-106. This article argues that the cumulative effects of environmental regulation have had a profound influence on housing costs. Offers several ways in which environmentalists and builders might cooperate to implement regulations that, while still effective in protecting the environment, would have less impact on housing affordability.

**Brooks, Mary E.** Housing Equity and Environmental Protection: The Needless Conflict. Washington, D.C.: American Institute of Planners, 1976. Addresses the issue of simultaneously pursuing national environmental objectives and housing goals. Although somewhat dated, this book provides an interesting perspective on this issue.

**Buck, Susan J.** Understanding Environmental Administration Law. Washington, D.C.: Island Press, 1991. Assembles relevant laws and discusses their administration and purposes. Provides a brief overview of the American legal system and then examines the history of environmentalism in the United States, the public policy process, legal concepts in environmental law, and international environmental issues.

**Carnegie Commission on Science, Technology, and Government.** Risk and the Environment: Improving Regulatory Decision Making. New York: Carnegie Commission On Science, Technology and Government, 1993. Examines a number of ideas for improving the federal government's infrastructure for environmental regulation. Offers suggestions for creating a more efficient and effective regulatory structure.

**Cawley, R. McGreggor.** Federal Land, Western Anger: The Sagebrush Rebellion and Environmental Politics. Lawrence, KS.: University Press of Kansas, 1993. An analysis of the Sagebrush Rebellion that began in Nevada in 1979 over federal land policy. Useful for understanding conservation goals and federal policy initiatives and their impact at the state level.

**Clark, Ray, and Larry Canter, ed.** Environmental Policy and the National Environmental Protection Act: Past, Present, and Future. Boca Raton, FL.: St. Lucie Press, 1997. Highlights historical trends, current issues, and future opportunities in the development of environmental policy in the context of NEPA. Examines how the Act has affected environmental policy and government decision making.

**Committee On Scientific Issues in The Endangered Species Act.** Science and The Endangered Species Act. Washington, D.C.: National Academy Press, 1995. A study by the National Research Council on scientific aspects of ESA to determine whether the Act protects endangered species and their habitats. Excellent overview of issues related to species definition, conservation conflicts between different species, habitat conservation, recovery planning, risk, and timing.

**Congressional Quarterly Researcher 5, no. 12 (March 31, 1994).** This entire issue of CQ Researcher is devoted to the twenty-fifth anniversary of the environmental movement in the United States. Contains articles dealing with the history of the movement, discussions of major environmental programs and organizations, and looks at the current movement to roll back environmental regulation.

**Conservation-Based Development Web Site.** Conservation-Based Development is an emerging field which seeks to promote environmental integrity, economic opportunity, and community vitality by recognizing that these three are inseparable goals which must be pursued hand-in-hand.

**Cothern, Richard, ed. Handbook for Environmental Risk Decision Making: Values, Perceptions, and Ethics.** Boca Raton, FL.: Lewis Publishers, 1996. Collection of papers presented at a one-day symposium in Washington, D.C. in 1994. Discussions relate to risk assessment, values, intergenerational equity, rationality in decision making, and ethics. Difficulties in reconciling gaps between public perceptions and scientific realities are examined from various analytical approaches.

**Dahl, Thomas E. Wetland Losses in the United States, 1780's to 1980's.** Washington, D.C.: U.S. Department of the Interior, Fish and Wildlife Service, 1990. A report to Congress by the Fish and Wildlife Service. Documents wetland losses over a 200-year period which result, for the most part, from areas drained for agricultural use.

**Dennison, Mark S. Environmental Considerations in Real Estate.** Chicago: Real Estate Education Company, 1994. Examines environmental laws and their impact on real estate operations. Discusses concepts such as due diligence, risk allocation, disclosures, and environmental liability insurance.

**Dennison, Mark S., and James F. Berry. Wetlands: Guide To Science, Law, and**

**Technology.** Park Ridge, N.J.: Noyes Publications, 1993. A guide to scientific, legal, and technical aspects of wetlands. Extensive coverage of Section 404 of the Clean Water Act and other environmental laws pertaining to wetlands.

**Dennison, Mark S., with contributions from James A. Schmid.** Wetland Mitigation: Mitigation Banking and Other Strategies for Development and Compliance. Rockville, MD.: Government Institutes, 1997. A guide to understanding and implementing mitigation measures required by development of wetlands. Covers regulatory aspects, permitting procedures, and steps in obtaining permit approvals. Case studies, checklists, and guides to state wetland offices are presented in a clear and easy-to-use reference format.

**Desiderio, Michelle and Michael Kirwin.** The Regulation of Solid and Hazardous Waste: A Builder's Guide. Washington, D.C., the National Association of Home Builders, 1994. A practical guide for builders and developers which answers the most often-asked questions about solid and hazardous waste at the jobsite.

**Diamond, Henry, and Patrick F. Noonan, ed.** Land Use in America. Washington, D.C.: Island Press, 1996. Broad overview of major land-use issues of the past twenty-five years. Presents a ten-point agenda for future action. Addresses issues of private property rights, takings, community-based actions through the lead of local governments, a broad overhaul of land development regulations, fair treatment of property owners, and better coordination of government policies that affect development.

**Downs, Anthony, "Growth Management: Satan or Saviour?** Regulatory Barriers to Affordable Housing," Journal of the American Planning Association 58, no. 4 (1992): 419-422. Argues that lack of affordable housing is not due solely to government regulation, that poverty is the primary cause. States that the Endangered Species Act and wetlands regulation are relatively minor contributors to the increase in house prices. Identifies local government ordinances, such as zoning and density regulations, as the true regulatory barrier to affordable housing.

**Echard, Jo Kwong.** Protecting the Environment: Old Rhetoric, New Imperatives. Washington, D.C.: Capital Research Center, 1990. Examines the intellectual foundations and political roots of the modern environmental movement. Questions the effectiveness of the traditional "command-and-control" approach to regulation and offers a free-market strategy as an alternative. Contains a particularly informative chapter on the evolution of property rights in the United States.

**Elliott, E. Donald,** "How Takings Legislation Could Improve Environmental Regulation," William and Mary Law Review 38, no. 3 (1997): 1177-1195. Argues that new takings legislation may actually strengthen environmental regulation efforts by clarifying environmental law. Counters the argument by environmentalists that such legislation will severely weaken regulation.

**Engel, David, Edwin Stromberg, and Margery Austin Turner,** "Toward A National Urban Environmental Policy," Cityscape: A Journal of Policy Development and Research 1, no. 2 (1996): 1-16. The authors contend that both environmental protection and housing and community development would be better served if the two factions involved came together to pursue their goals in an integrated fashion. Presents cogent points from both sides of the environmental/development controversy.

**Ercmann, Sevine,** "Enforcement of Environmental Law In United States and European Law: Realities and Expectations," Environmental Law 26, no. 4 (1996): 1213-1239. Suggests alternative means of environmental enforcement: reports that the traditional command-and-control method is giving way to more innovative strategies such as eco-contracts and environmental auditing, which are proving successful.

**Evans, Brock,** "An Environmentalist's Response To 'Environmental Regulation and Housing Affordability,' " Cityscape: A Journal of Policy Development and Research 1, no. 2 (1996): 107-114. In this rebuttal to an article by Frank Branconi (q.v.), Evans refutes the statistical basis of

Branconi's conclusions and argues that when demographic shifts are factored into the environmental regulation/house price equation, the correlation between the two is actually quite small.

**Fogleman, Valerie M.** Guide to the National Environmental Protection Act: Interpretations, Applications, and Compliance. New York: Quorum Books, 1990. Presents NEPA in a readable format. Designed to be a practical guide to compliance.

**Gebhardt, Karl, and others, ed.** Riparian and Wetland Classification Review. Denver, CO.: United States Department of the Interior, Bureau of Land Management Service Center, 1991. Introduces major concepts relevant to understanding riparian systems and reviews selected riparian and wetland classification schemes.

**General Accounting Office.** Environmental Protection: Challenges Facing EPA's Efforts to Reinvent Environmental Regulation: Report to Congressional Requesters. Washington, D.C.: General Accounting Office, 1997. Outlines EPA's program to reinvent environmental regulation. Examines various issues which make these attempts at fundamental restructuring difficult.

**Godschalk, David,** "In Defense of Growth Management," Journal of the American Planning Association 58, no. 4 (1992): 422-424. Argues in rebuttal to the article by Anthony Downs (q.v.) that local regulation is essential and that, due to the nature of the private builder industry, deregulation would not result in an increase in the supply of affordable housing.

**Goldstein, Jon H., and William D. Watson,** "Property Rights, Regulatory Taking, and Compensation: Implications for Environmental Protection," Contemporary Economic Policy 15, no. 4 (1997): 32-42. Discusses property rights and compensation in the context of environmental regulation.

**Gonzales, Helen,** "Increasing Water and Sewer Rates: A New Crisis For The Poor," Clearinghouse Review 29, no. 4 (1995): 409-417. Examines compliance costs of the Clean Water Act and the impact of such costs on low-income families. Provides interesting statistics on household income and expenditures for water/sewer services. This article shows how essential regulation can have negative social effects.

**Gorczynski, Dale M.** Insider's Guide to Environmental Negotiation. Chelsea, MI.: Lewis Publishers, 1991. Outlines strategies and techniques for participating in environmental negotiations. Discusses public and private negotiations, the role of the media, lawyers and lobbyists, elected officials, and others. Stresses the unique nature of environmental negotiations. A very useful and practical guide.

**Gyourko, Joseph, and Peter Linneman,** "The Affordability of the American Dream: An Examination of the Last 30 Years," Journal of Housing Research 4, no. 1 (1993): 39-72. Examines changes in housing affordability over the last thirty years. Concludes that for low-income and less educated households housing has become less affordable due to falling income levels.

**Hamilton, Michael S., ed.** Regulatory Federalism, Natural Resources, and Environmental Management. Washington, D.C.: American Society For Public Administration, 1990. Posits that there is more than one way to pursue environmental regulatory goals, that traditional methods are not necessarily the best avenue. Asserts that intergovernmental environmental management is an effective, efficient alternative. Examines shortcomings of the current federalist strategy.

**Hammer, Donald A.** Creating Freshwater Wetlands. Boca Raton, FL.: CRC Press, 1997. This revised manual outlines wetland regulations and restoration procedures with an emphasis on the processes used to create freshwater wetlands. Appendices include references for further reading, contact information for equipment and vegetation suppliers, and resources for courses, workshops, and newsletters.

**Hanna, Susan, Carl Folke, and Karl-Gooran Moaler, ed.** Rights To Nature: Cultural,

Economic, Political, and Ecological Principles of Institutions for the Environment. Washington, D.C.: Island Press, 1996. A multidisciplinary examination of issues related to property rights and environmental management with perspectives from fields including anthropology, economics, law, political science, and sociology. The overriding issue is one of developing property rights systems with a larger context of equity, sustainability, and efficiency.

**Hatchett, David L.,** "Regulation of Construction Site Stormwater Runoff: We Can Do Better Than This," Indiana Law Review 29, no. 1 (1995): 153-177. Identifies sediment from construction site runoff as a major component of non-point source water pollution. Argues that current stormwater controls are not effective, and offers ideas on how these controls might be made more efficient and effective.

**Helvarg, David,** "The War on The Greens," The Nation, 28 November 1994. This article recounts episodes of the violence which has become part of the anti-environmental backlash. Discusses the history and philosophy of the so-called "Wise-Use" movement, the most extreme of anti-environmental groups in the United States.

**Henning, Daniel H., and William R. Mangum.** Managing the Environmental Crisis: Incorporating Competing Values In Natural Resource Administration. Durham, N.C.: Duke University Press, 1989. A basic, introductory text in environmental policy and administration which emphasizes comprehensive, conceptual, interdisciplinary approaches to environmental administration. Addresses such topics as land use planning, suburban sprawl, growth controls, and zoning.

**Hoffman, J., Max H. Bazereman, and Steven Yaffee,** "Balancing Business Interests and Endangered Species," Sloan Management Review 39, no.1 (1997): 59-73. Argues that economic costs of environmental protection are often overstated while benefits are understated. Examines specific means by which both the environment and the economy may be protected.

**Jackson, Thomas C.** Developer's Guide to The Endangered Species Act. Washington, D.C.: Homebuilder Press, 1996. A practical guide for builders and developers which answers the most often asked questions regarding ESA.

**Kaufman, Wallace.** No Turning Back: Dismantling the Fantasies of Environmental Thinking. New York: Basic Books, 1994. Written by a former leader in the environmental movement, this book challenges many of the assumptions underlying current environmental policies and goals. Provides compelling evidence to view claims of environmental devastation and damage with suspicion.

**Kentula, Mary E., and Ann J. Hairston, ed.** An Approach To Improving Decision Making in Wetland Restoration and Creation. Boca Raton, FL.: C.K. Smoley, 1993. Produced by the United States Environmental Protection Agency's Wetlands Research Program, this book details techniques used to compare wetland mitigation projects and natural wetlands. Topics covered include analysis of wetlands data, such as permitting trends; monitoring strategies, and use of data to improve mitigation projects.

**Koebel, C. Theodore, and Kristina Zappettini,** "Housing Tenure And Affordability from 1970 to 1990: Progress, Stasis, or Retreat?" Housing and Society 20, no. 3 1993): 35-46. Assigns causality for the decline of housing affordability to long-term demographic and financial cycles.

**Kone, Linda.** Land Development. Washington, D.C.: Homebuilder Press, 1994. A comprehensive guide to issues involved in land development. Includes a chapter on environmental regulations affecting land development.

**Kusler, Jon A., and Teresa Opheim.** Our National Wetland Heritage: A Protection Guide. Washington, D.C.: Environmental Law Institute, 1996. A guidebook for those interested in protecting wetlands. Contains background information on characteristics and origins of wetlands; management and protection issues; federal, state, and local regulations; and nonregulatory approaches to wetlands.

**Lambert, Thomas.** The Endangered Species Act: A Trainwreck Ahead. St. Louis: Center for the Study of American Business, Washington University, 1995. This short book attempts to predict and quantify future effects of ESA.

**Leitch, Jay A., and Herbert R. Ludwig, comp.** Wetland Economics, 1989-1993: A Selected Annotated Bibliography. Westport, CT.: Greenwood Press, 1995. Lists materials providing an overview of economic perspectives on wetland issues with foci on subjects areas including methodological, empirical, restoration and creation, and delineation and definition. The book's overall focus is on wetland economic assessment and valuation and related policy issues.

**Lester, James P., ed.** Environmental Politics and Policy: Theories and Evidence. Durham, N.C.: Duke University Press, 1995. Highlights the work of political scientists dealing with environmental politics and policy. Contains an excellent historical analysis of the conservation and environmental movements, examines federalism and environmental policy, and public perceptions of environmental policies.

**Linneman, Peter, and Issac F. Megbolugbe,** "Housing Affordability: Myth or Reality?" Urban Studies 1, no. 29 (1992): 369-392. Convincingly argues that the issue of housing affordability is partly real and partly manufactured.

**Lueder, Diane, Daryl O. Cooper, and Michael Greely,** "Impact Fees: Who Pays For Community Development?" Illinois Libraries 78, no. 1 (1996): 23-25. Briefly examines the debate over impact fees, the rationale behind their implementation, and the means by which they are properly assessed and used.

**Lund, Eric and Peter Yost,** Residential Construction Waste Management, A Builder's Field Guide, How to Save Money and Landfill Space. National Association of Home Builders Research Center, Upper Marlboro, Md., 1997. A field guide booklet with information on cost-effective and voluntary construction waste management including developing a waste management plan and reducing framing waste.

**Lyon, John Grimson.** Practical Handbook for Wetland Identification and Delineation. Boca Raton, FL.: Lewis Publishers, 1993. Presents background information related to wetlands, including federal definitions and criteria for wetlands identification. Provides methods for delineating wetlands, from routine investigations to higher levels of detail that are used in preparing a wetlands report. Bibliography includes wetland and plant literature. Appendices include data sources and sample wetland reports.

**Malizia, Emil, Richard Norton, and Craig Richardson,** "Reading Writing, and Impact Fees," Planning 63, no. 9 (1997): 17-19. Although pertaining specifically to the use of impact fees to finance new school construction, this article offers a good basic overview of the impact fee concept and their implications for the residential construction industry.

**Malpezzi, Stephen,** "Housing Prices, Externalities, and Regulation in U.S. Metropolitan Areas," Journal of Housing Research 7, no. 2 (1996): 209-241. Analysis various factors that determine house prices, with a focus on the role of regulations. Although this article does not consider federal environmental regulations, it does conclude that the broad scope of local regulations contributes to increasing house prices.

**Manley, Marisa,** "A Victim of Wetlands Regulation," The Freeman, 1 July 1997. This article relates the story of a large Maryland developer's involvement with the wetlands provisions of the Clean Water Act.

**Marsh, Lindell, Douglas Porter, and David Salvesen,** "The Impact of Environmental Mandates on Urban Growth," Cityscape: A Journal Of Policy Development and Research 1, no. 2 (1996): 127-154. Outlines a number of ways in which the environmental/development gap might be bridged. Focuses on standardization of the planning process as a means of accomplishing this.

**Meeks, Carol B.,** "Balancing Regulation and Affordable Housing," Journal of Family Economic

Issues 13, no. 4 (1992): 373-382. Examines a number of types of regulations perceived as affecting the production of affordable housing.

**Meyer, Stephen,** "The Economic Impact of the Endangered Species Act on the Housing and Real Estate Markets," New York University Environmental Law Journal 6, no. 2 (1998): 450-479. Provides empirical evidence to demonstrate that the Endangered Species Act has not negatively affected the housing and real estate markets. Asserts that increasing numbers of species being listed is due not to more and more habitat being affected by ESA, but to the fact that development is continuing to encroach on existing habitat.

**Mintz, Joel.** Enforcement at the EPA: High Stakes and Hard Choices. Austin, TX.: University of Texas Press, 1995. An examination of the enforcement of federal environmental standards by the EPA. A critical look at public expectations of that agency in the light of funding levels and political realities.

**Monks, Vicki,** "Environmental Regulations: Who Needs Them?" National Wildlife 34, no. 2 (1995): 25-30. This insightful piece offers several case studies showing the necessity of environmental regulation. An emphasis is on the empowerment of the average citizen under these regulations to participate in their enforcement.

**Morandi, Larry,** "Tilting At Windmills?" State Legislatures 22, no. 9 (1996): 23-26. Examines innovative environmental regulatory practices used in Holland and the potential for their application in the United States.

**National Association of Home Builders.** The Truth About Wetlands. Washington, D.C.: National Association of Home Builders, n.d. Discusses perceived problems in the wetlands provisions of the Clean Water Act.

**National Association of Home Builders.** The Truth About the Endangered Species Act. Washington, D.C.: National Association of Home Builders, n.d. Concludes that ESA does not work and that it is inequitable as regards its impact on landowners.

**National Association of Home Builders.** The Truth About Property Rights. Washington, D.C.: National Association of Home Builders, n.d. Examines the property rights issue and calls for a more equitable system of environmental regulation.

**Nolon, John R.,** "The National Land Use Policy Act," Pace Environmental Law Review 13, no. 2 (1996): 519-523. In examining the failed Land Use Policy Act of 1970, this article lays out several important lines of consideration for future land use policy that would be more balanced and fair.

**Oates, Wallace E.,** "Thinking About Environmental Federalism," Resources 130 (winter 1998): 14-16. Examines issues in the debate over whether environmental regulation should be the province of the federal government or the states.

**Office of Management and Budget.** Report to Congress on the Costs and Benefits of Federal Regulation. Washington, D.C.: Government Printing Office, 1997. This draft of a report to Congress concludes that the benefits of environmental regulation exceed the costs. Also contains an interesting and useful history of regulation and the regulatory process in the United States.

**Olenik, Thomas J., and S.L. Cheng,** "Land Development Regulations: Roadblock to Affordable Housing," Journal of Urban Planning and Development 120, no. 1 (1994): 22-27. Argues that environmental regulations must be curtailed if affordable housing is to be provided. Outlines a number of environmental regulations in the state of new Jersey seen as adding to the increase in housing cost.

**Ordway, Nicholas, Jack P. Friedman, and Jack C. Harris,** "How the Federal Regulations Cycle Affects the Real Estate Industry," Real Estate Issues 20, no. 3 (1995): 40-46. Looks at the process by which regulations can change over time as they pass through a set of well-defined stages. This process of evolution may result in regulations that, although conceived and implemented with all good intentions, become inefficient, unfair, and/or ineffective.

**Pethis, Rudiger.** Valuing the Environment. Dordrecht; Boston: Kluwer Academic Publications, 1994. Addresses theoretical issues involved in determining the value of the environment.

**Polasky, Stephen, and Holly Doremus,** "When the Truth Hurts: ESA Policy on Private Land With Imperfect Information," Journal of Environmental Economics and Management 35, no. 1 (1998): 22-47. Discusses the role of information collection in the ESA listing process and the use of compensation as an incentive for landowners to participate.

**Porter, Douglas, and David A, Salvesen, ed.** Collaborative Planning for Wetlands and Wildlife: Issues and Examples. Washington, D.C.: Island Press, 1995. A study of limitations of regulatory approaches to wetlands and wildlife protection with examples of community approaches to reconciling environmental protection goals and development. Case studies focus on the use of Special Area Management Plans (SAMP), experiences with this approach, and remaining obstacles.

**Profeta, Timothy H.,** "Managing Without A Balance: Environmental Regulation in Light of Ecological Advances," Duke Environmental Law & Policy Forum 7, no. 1 (1996): 71-103. Argues that current environmental regulation must be changed to reflect recent advances in the field of ecology.

**Repetto, Robert, Roger C. Dower, Robin Jenkins, and Jacqueline Geogegan.** Green Fees: How A Tax Shift Can Work for the Environment and the Economy. Washington, D.C.: World Resource Institute, 1992. Outlines a strategy whereby governments could generate tax revenues more efficiently through the use of "green fees" such as charges on pollution, waste, and traffic congestion. Has implications for developers because such taxes could, at least in part, replace impact fees as a source of revenue generation by local governments.

**Robbins, Carol T.** Removing Regulatory Barriers to Affordable Housing: How States and Localities Are Moving Ahead. Washington, D.C.: United States Department of Housing and Urban Development, Office of Policy Development and Research, 1992. Discussions of actions taken by state and local governments to reduce regulatory burdens and their associated costs in housing development. Cluster development, reduced lot sizes, impact fee reforms, and changes in restrictive local ordinances are among the initiatives presented.

**Rothstein, Richard,** "Conceding Success," The American Prospect 29 (November- December 1996): 82-87. This article refutes the argument that environmental regulations implemented in the United States over the last twenty-five years have been generally ineffective. Gives a number of concrete examples of how regulations have improved the quality of the environment.

**Runyon, L. Cheryl, and John Helland.** Wetlands Mitigation and Mitigation Banking: Reducing the Impact of Development on Wetlands. Denver; Washington, D.C.: National Conference of State Legislatures, 1995. A concise guide to issues surrounding wetlands protection and options for mitigation banking. Includes case studies of state experiences with this concept. Appendices include state statutes that govern wetland mitigation banking, state agency regulations and guidelines that govern them, and existing and proposed banks.

**Salvesen, David.** Wetlands: Mitigating and Regulating Development Impacts. Washington, D.C.: Urban Land Institute, 1994. Good general overview of the nature of wetlands. Discusses regulations, the permitting process under relevant sections of the Clean Water Act, the takings issues, mitigation of development impacts, regional wetlands planning, and state wetlands regulations.

**Scodari, Paul F.** Measuring the Benefits of Federal Wetlands Programs. Washington, D.C.: Environmental Law Institute, 1997. An analytical approach to measuring benefits of wetlands protection. Forgone development benefits are also examined and are linked to house price increases that result from land-use restrictions.

**Shaw, Jane S.,** "Environmental Regulation: How It Evolved and Where It Is Headed," Real Estate Issues 21, no. 1 (1996): 4-9. This article examines the genesis of environmental regulation in the United States and discusses regulatory programs seen as having a negative affect on the real estate industry.

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**Smith, Chris,** "Greening the Economy: Economic Advantages of Environmental Protection," New Statesman & Society 9, no. 390 (1996): 26-27. Asserts that the typical stance of "environment versus jobs" is skewed. Provides examples of situations where corporate dedication to the environment has resulted in increased employment and productivity.

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NATIONAL ASSOCIATION OF HOME BUILDERS

## SMART GROWTH CASE STUDY: VILLAGE HOMES

Normal View

### A Green Building/Cluster Development Project

**Davis, Califorina**

In 1973, Judy and Michael Corbett conceived of a unique development to be built on property adjacent to the University of California at Davis, 14 miles west of Sacramento. Inspired by their academic work in ecology and by UC-Davis's commitment to conservation and reduced dependence on automobiles, the Corbetts sought to acquire 60 acres of tomato fields--located 15 minutes by bicycle west of downtown Davis--as the site for an ecologically sensitive, energy-efficient development.

The Corbetts were motivated not only by issues of environment and energy but also by the potential of the site planning and land development processes to foster a sense of community and neighborliness. Together, they undertook construction of Village Homes, which has been referred to as "one of the world's best examples of sustainable development."

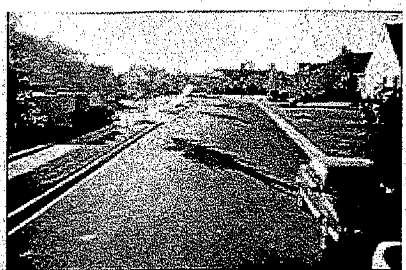
For the Corbetts, the keys to environmental responsibility were perceived as maintenance of agricultural productivity, minimization of rainwater runoff (and the piped systems commonly accommodating it), reduction of automobile travel by promoting walking and cycling, and the use of solar energy. The key to a sense of neighborliness being frequent face-to-face participation in activities of mutual interest, the Corbett's predicated Village Homes on the active involvement of residents in the planning and ongoing operations of the community, attraction of a community of residents--with wide-ranging incomes--committed to preservation of the environment and energy conservation, and development of a mutual stake through common ownership of valued facilities and income-producing properties.

Realization of the Village Homes concept was difficult. The proposal called for areas designated for permanent agricultural use, neighborhood commercial services, a broad range of housing prices, solar-heated homes, and rental apartments as well as single-family units. With its unusual approach to land development, the project met with rejection by no less than 20 lenders. Finally, by failing to mention the experimental nature of their proposal and the somewhat controversial ecological basis for their design, the Corbetts obtained financing from Sacramento Savings and Loan and, in 1975, took title to the property and began construction. The result was an unprecedented, 60-acre, solar community featuring community gardens, orchards, vineyards, 220 single-family detached homes, and 24 rental apartment units.

Village Homes is a single superblock focused on a village green--a central open space with adjacent commercial, community, and recreational facilities. The commercial center consists of 21 businesses and a restaurant. The community center provides a daycare facility and a small suite of offices with rental apartments above. The recreation center includes a solar-heated swimming pool and meeting rooms. A home owners' association owns all three centers. The commercial facilities, together with apartments owned by the association and the space leased for the daycare center, provide the association with income to maintain and enhance neighborhood services and amenities.

Arlington Avenue wraps around the Village Homes superblock, bounding it on the north and east. This primary access street feeds into 20- to 26-foot-wide east/west cul-de-sacs that serve clusters of residences separated by greenbelts. Homes are located along the cul-de-sacs in groups of eight and focus on rear yards that open onto larger common areas leading to the village green.

Forty percent of the 60-acre site is dedicated to agriculture and green space. Twenty percent (12 acres) comprises perimeter greenbelts used for gardens at the community's western boundary and for orchards abutting Arlington Avenue at the community's northern and eastern boundaries. Between and among the residential units another 20 percent (12 acres) of the site is dedicated to greenways and vineyards. Bicycle and pedestrian paths located in the internal greenways permit travel throughout Village Homes without crossing a street and connect with bikeways leading to the UC-Davis campus and downtown Davis.



The use of narrow residential streets held the land needed for streets to just 20 percent, thus reducing construction and maintenance costs, limiting summer heat buildup on the site, and minimizing runoff. In lieu of piped storm drains, the site uses natural swales, with the land shaped to distribute excess water over the porous soils to irrigate agricultural areas. The city's planning review board was originally so skeptical of this innovation that they required the Corbetts to place a performance bond on the stormwater system. They got the bond back quickly, however, when a 100-year flood occured several years later and the system handled not only its own stormwater, but the run-off from several neighboring developments whose traditional stormwater systems backed up.

All of the homes in Village Homes are solar heated through passive or active systems and most have solar water heaters. Wide but shallow single-family lots (many 85 feet wide by 50 feet deep) line the east/west cul-de-sacs and provide narrow eastern and western exposures and a broad southern exposure. This arrangement permits the capture of winter solar heat in south-facing glass-enclosed solaria. Energy use at Village Homes totals one-third to one-half that of other developments of comparable size.

Single-family units at Village Homes range from a few 600- to 1,000-square-foot units and a cooperative house for nine residents to accommodate low-income individuals, to homes that exceed 2,000 square feet. By 1980, 160 single-family units and ten apartments had been built, with single-family units ranging in price from $35,000 to $150,000, but the majority between $70,000 and $90,000. A 2,200-square-foot home built in 1980 and priced at $90,000 sold for $350,000 in 1999. Most units at Village Homes sell for $11 per square foot more than homes of comparable size in surrounding areas.

Not all of the original design premises and expectations of Village Homes have been realized. The Davis Department of Health rejected a plan to recycle gray water for irrigating orchards. A cooperative store idea fell by the wayside, as did a central cooperative elementary school. And when federal tax credits for alternative power sources were terminated by the Reagan Administration in the 1980s, continued solar development on the Village Homes model experienced a major setback.

Nonetheless, Village Homes has dealt effectively with reducing reliance on the automobile, creating community interaction, limiting infrastructure costs, using natural systems, and conserving energy. It has proved that provision of small-scale commercial and office space and integration of agriculture, rental apartments, and lower-income housing in a single-family-dominant, 60-acre development designed for energy efficiency and ecological integrity is both functional and economically feasible.

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# SMART GROWTH CASE STUDY: GARNET OAKS

Normal View

## A Green Building/Cluster Development Project

**Bethel Township, PA**
*Garnet Oaks exemplifies the best use of cluster development techniques to preserve open space and environmentally sensitive areas. The smaller lot sizes that resulted from this plan were not a deterent to sales. Rather, sales were brisk and prices rose significantly during build out of the development.*

**Features:**

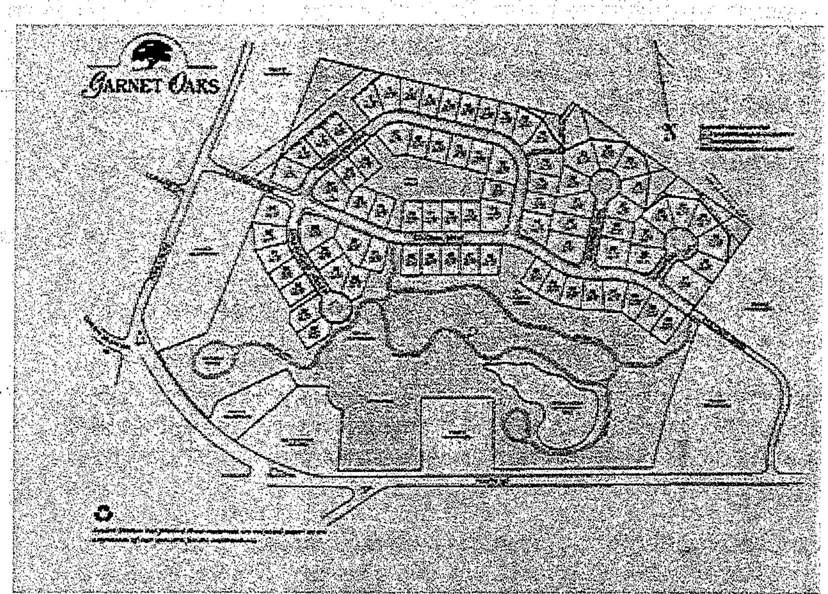
- 80 homes on 58 acres
- 51% of land preserved as open space
- Cluster development
- Preservation of woodlands and specimen trees
- Preservation of structures from original estate.

Consumer focus groups conducted by Raelen Homes, a builder and developer based in Ambler, PA. revealed nearly unanimous agreement that mature landscaping and the look of an established neighborhood are critical considerations in home purchase decisions.

To compete more effectively with older, existing communities, Realen Homes is devoting considerable effort to preserving trees, particularly specimen trees, thereby creating a more mature and established character in their new neighborhood. Realen believes that trees make an invaluable contribution to a community's sense of stability and maturity. Realen's tree preservation effort is a logical extension of the firm's goal to establish itself as a "green" builder of national repute.

In developing the land plan design criteria for Garnet Oaks, Realen Homes focused on the results of one of its buyer satisfaction surveys. One-fifth of survey respondents indicated that Realen's new communities needed more trees, open space, and "natural landscaping".

Garnet Oaks consists of 80 single-family home sites on 58 acres in Bethel Township, Delaware County, Pa. The original site—hilly and heavily wooded—featured trees at least 40 years old, five acres of forested wetlands with a variety of ferns and sedges, and remnants of a bank barn, silo, stone wall, and overgrown tree-lined lane. The site's marketing and development activities have concentrated on tree preservation, a strategy that represents a departure from the norm for Realen.




Realen set out to maintain the site's character by:

- obtaining a rezoning for the site to allow the clustering of homes, thereby preserving 51 percent of the tract in open space;
- undertaking careful environmental planning and site analysis to design roadways, utilities, and home sites around the open space;
- preserving woodlands as well as specimen trees that once lined a 200-year-old farm lane;
- uncovering and preserving a stone wall and spring house from the site's original estate;
- protecting wetlands through coordinated permitting with state and federal regulatory agencies; and
- developing a tree protection training manual and course in conjunction with the Morris Arboretum of Chestnut Hill, Pa. for subcontractors involved in the Garnet Oaks project.

A site analysis identified the areas best suited for development as well as the sensitive areas to be left undisturbed, including steep slopes, buffer areas adjoining wetlands, prime recreation areas, perimeter buffer areas, and specimen trees. Home sites were clustered to capitalize on the several unique open space features. Reduced lot sizes of approximately one-quarter acre (minimum lot size 10,000 square feet) permitted what would typically have been excess private lot area to become common wooded open space, providing home owners with greater privacy.

Tree preservation was the guiding principle behind many of the innovative land planning and construction techniques incorporated into Garnet Oaks. Before the design phase, the development team located specimen trees through aerial photography and field surveys and analyzed grading to minimize adverse effects on trees. Sequentially numbered clearing limit stakes were used to prevent accidental clearing while tree protection fences and signage throughout the site minimized damage to tree roots. Before the start of construction, an arborist trimmed tree limbs to prevent damage to trees slated for preservation. All subcontractors were required to attend the tree protection training course.

Road alignment design during the planning stage respected topographic constraints and followed the old treelined farm lane. Township approval for tree islands within cul-de-sacs permitted increased island size and saved more trees. Sidewalks that follow a serpentine path through the open space saved still more trees.

Negotiations with PECO Energy, the local utility, led to utility installation modifications that prevented damage to mature trees. Typically, the utility company installs gas lines on a particular side of the street behind the sidewalk. Field design changes moved the gas line to the other side of the street where it would not conflict with specimen trees. In addition, gas and electric lines were installed just behind the curb in some locations instead of behind the sidewalk. Further, a portion of one roadway was realigned to avoid any interference with tree roots.

An in-stream storm water management system was designed to reduce the clearing requirements associated with a typical detention basin. The system allowed for the preservation of two acres of woodlands that would have otherwise been cleared.

All construction encroachments into wetlands were avoided except for a .10-acre segment. In addition, a wetlands mitigation plan called for the dispersion of storm water into a woodland area to create forested wetlands and eliminate the need for additional clearing.

Open space amenities within the development attest to the massive tree and site preservation effort at Garnet Oaks. The plan includes a nature trail system that will wind through the preserved wooded area and include boardwalks in certain areas to allow pedestrians to view areas that would otherwise remain inaccessible. A local Boy Scout troop is building the trail.

The history of the site is reflected in the preservation of an old stone silo foundation and spring house, which also function as unique landscape features. A large wooded area has been named the Rachel White Preserve in honor of the farm estate that once occupied the site. The site's natural and historic elements are highlighted in a nature trail guide that doubles as a marketing piece for Garnet Oaks.

The relatively smaller lot sizes at Garnet Oaks as compared to competitors' offerings have not slowed sales. Since opening in January 1993, fifty-five homes have been sold. Sixty-five percent of the lots directly abut open space, giving them the appearance and privacy of a larger lot. In five cases, wide bands of treed open space dominate the streetscape and connect larger open areas with the neighborhood sidewalk system. A picnic grove and a tot lot featuring unique play equipment further enhance community open space.

By late 1994, home prices ranged from $218,900 to $245,900, an increase of $24,000 from the base price offered during presales in January 1993. Current lot premiums range from $2,000 to $8,000 and are based largely on the lot size and proximity to open space.

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## SMART GROWTH CASE STUDY: THE PRESERVES AT HUNTER'S LAKE

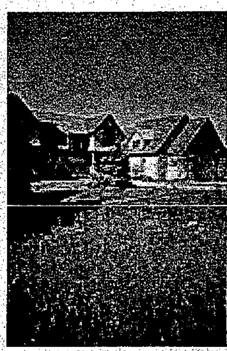
Normal View

### A Green Building/Cluster Development Project

**Ottawa, Wisconsin**

*Southeastern Wisconsin's scenic rolling hills provide the setting for The Preserve at Hunter's Lake, developed by Siepmann Realty Corporation of Waukesha, Wisc., a model project that features open space conservation.*

The Preserve permanently reserves large areas of buildable upland woods and prairies, steep slopes, wetlands, and shoreland for the enjoyment of its home owners. A one-mile segment of the 1,000-mile-long Ice Age National Scenic Trail winds its way through the undulating terrain within the community's common area and connects to private subdivision trails.



Located in the town of Ottawa, in Waukesha County, Wisconsin, The Preserve at Hunters Lake includes 41 one-and-one-half-acre lots surrounded by over 185 acres of permanently preserved open space. The land, which was farmed in the mid-1850s by the Hunter family from Ireland, has a rich history. In addition to farming the land, the Hunters built a beautiful small lannon stone mansion and established a small stone quarry to serve the area building industry.

By the early 1900s, the quarry closed and a prominent Milwaukee brewing family took over the farming operation. In the mid-1900s, the land was left fallow, giving way to native prairie flowers and towering hardwoods. The 285-acre site includes three-fourths of a mile of undeveloped shoreline on Hunters lake, a small stream-fed lake. The shoreline encompasses over 65 acreas of wetlands marshes that are part of The Preserve. It was around these woods, prairies, and wetlands that The Preserve was designed and built in 1994.

**Planning and Design**

Not only did the site's terrain pose a challenge to the development's design, but the location of the proposed community about 40 minutes farther west than most people were believed to prefer. Accordingly, the goal was to create a community that would take advantage of the site's interesting natural features by preserving them and surrounding them with homesites. In particular, the Kettle Moraine area, with its steep glacial hills, thick forests, and broad vistas, is an attractive setting for new homes.

When planning and designing the home sites, the design team—Ron and Jim Siepmann of Siepmann Realty Corp., Nicholas R. Patera of Teska and Associates, Inc., of Evanston, Illinois, and engineer Jerry Wegner of Jahnke & Jahnke Associates of Waukesha, Wisconsin—carefully considered the site's large inventory of special landscape features. Under Wisconsin environmental law, the wetlands, wooded ridge, and steep slopes that make up a large portion of the site are designated a Primary Environmental Corridor. Surrounded by woods, the remaining small meadows and hayfields provided excellent building sites that did not require wholesale deforestation.

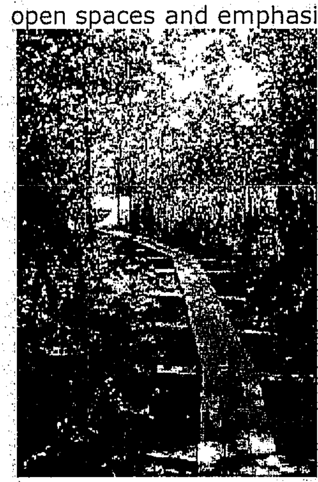
Each lot sits within a small cluster of six or fewer home sites that nestle up to woods. Each home owner enjoys a sense of neighborhood, yet a walk out the back door gives the impression that individual residents own several acres on undisturbed land. Buyers are encouraged to let their landscape naturalize and enhance it with native plantings, thus minimizing the area devoted to manicured lawns and respecting The Preserve's philosophy. The project's objective of low-density, clustered home sites and preserved open spaces serves as a model for regional and state officials who applaud The Preserve for preventing urban sprawl from destroying the countryside.

Under most circumstances, landscaping is a primary issue for the developer. At The Preserve at Hunters Lake, however, the natural landscape stands on its own. Trees within rights-of-way were transplanted to common areas and cul-de-sac islands; in fact, a sumac grove became the center of one cul-de-sac. Where the development's main road crossed Scuppernong Creek, wetlands plants were stored in a wetlands nursery for transplanting after road construction.

Roadways are lined with curb and gutter to reduce the need for ditches through the wooded area and to save a greater number of trees. The developer took great care during the tree-clearing operation to remove the minimum number of trees. Some roads were even realigned during construction to accomodate healthy or large trees within the right-of-way. In an effort to duplicate the original stone fences found throughout the farm, the entryway monuments are landscaped with native plantings.

**The Farmstead**

The unique farmstead provided the developer with many special features to be preserved as amenities for the home owners. A stone caretaker's cottage was restored and converted into a neighborhood gathering place, complete with a children's play area. The Hunter family's original farmhouse, dating to the 1850s, was entirely rehabilitated and meticulously finished. Road layouts were changed to save an old barn and silo, which became an aesthetic centerpiece for the neighborhood. Rustic split rail fencing and naturalized landscaping were added along many of the roadways to delineate the open spaces and emphasize the rural atmosphere.



Lengthy hiking trails connect home owners to other neighborhood clusters within the development, to a large segment of the Ice Age National Scenic Trail, and to a boardwalk that leads to the lake shore. The boardwalk provides access to paddleboats and canoes owned by the home owners' association. A self-guided nature tour identifies many native plant species along the boardwalk's meandering route through a sedge meadow, a calcareous fen, and an aspen and tamarack marsh.

**Marketing and Management**

Architectural plans for proposed homes must meet the developer's criteria regarding floor space (minimum 3,000 square feet), design (traditional styling and materials), roofs (cedar shakes), and natural materials (wood, stone, brick, or stucco on exterior walls). Homes built in The Preserve at Hunters Lake range from 3,000 to 7,000 square feet, typically with four to five bedrooms.

Sales at The Preserve have been strong, considering that lot prices—ranging from $80,000 to $125,000—are comparable to prices for three- to ten-acre sites in the area. When purchasing a lot in The Preserve at Hunters Lake, potential buyers are won over by the fact that they own over 185 acres, yet need tend only their own one-and-one-half-acre lot. The open spaces, amenities, and rural character of the development are strong marketing advantages, a philosophy used by Siepman Realty for many years. Private wells and on-site sewage disposal systems are necessary for each home site.

The open space, clustered-lot philosophy translates into minimal maintenance of natural areas and reasonable home owners' association fees. In addition, the preservation philosophy meant that widespread grading was unnecessary during construction. The compact pattern allowed street lengths and infrastructure runs to be shortened. All of these factors are important in the approval process—not just to the municipality, but also to surrounding home owners.

In a traditionally conservative area, the notion of upscale homes on lots smaller than three acres was risky, especially given the distance to downtown Milwaukee. The success of The Preserve at Hunters Lake has demonstrated, however, that the market will accept smaller lots that enjoy access to permanently preserved open areas.

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# SMART GROWTH CASE STUDY: THE FIELDS OF ST. CROIX

Normal View

## A Green Building/Cluster Development Project

**Lake Elmo, Minn.**

*The Fields of St. Croix is a conservation community located in the city of Lake Elmo, Minn. just 20 minutes northeast of the St. Paul central business district. The site plan preserves significant open space that includes farmland, organic farming, and restored native prairie.*

The "small town" atmosphere and services of the nearby lake Elmo Village Center, proximity to the historic city of Stillwater, and the natural beauty of the St. Croix River Valley make the Fields of St. Croix an exceptional place to live.

Robert Engstrom Companies, the developer of the Fields of St. Croix, assembled the 226-acre site from three owners. Inspired by its recent completion of Cloverdale Farm, a 250-acre community of upper-bracket homes adjacent to the Fields, the Engstrom Companies set out to develop an environmentally sensitive alternative to the customary large-lot subdivision characterized by 2.5- and 10-acre lots.

With Engstrom's submission of a concept plan that proposed cluster development at the Fields, the city of Lake Elmo took the cluster concept a step further and considered its application to a larger area. After 18 months of study and deliberation, Lake Elmo passed an open space development ordinance that governs 4,400 acres. The ordinance provides a base density of six dwelling units per 20 acres with a density bonus for features such as common greens, pathways, and historic preservation.

The final development plan for The Fields of St. Croix allocates more than 60 percent of the community's land to permanent open space comprised of farmland, a tree nursery, horticultural gardens, wooded slopes, two ponds, and restored native prairie. The farmland along State Highway 5 is retained as permanent open space that preserves the heavily trafficked highway view corridor. At the same time, home sites are clustered near a wooded ridge overlooking the site's ponds and open space.

The first phase of 45 home sites underwent development during the summer of 1997, and the market response was excellent; 80 percent of the home sites sold within six months. A second phase with approximately the same number of housing units was completed in 1999. The lot sites are affordable, varying in price from $44,500 to $150,000.

Innovative environmental and sustainable features that distinguish The Fields of St. Croix include the following:

- The first large-scale cluster development in Minnesota that provides an example of an economically viable and marketable alternative to land-consuming and unattractive large-lot subdivisions.
- A constructed wetlands wastewater system that provides central collection and environmentally compatible on-site treatment.
- Natural Harvest CSA, a community-supported agriculture farm that each week provides organically grown fresh vegetables, fruits, and flowers to resident and non-resident subscribers.

- The preservation and restoration of an historic Civil War-era barn to be owned by the community association and used as a community center and gathering place;

- Energy-efficient homes built according to the standards of the Energy Star Program of the U.S. Environmental Protection Agency and the Premier Homes Program of Northern States Power, the local utility company.

- Thirty acres of prairie restoration featuring native plants indigenous to the area.

- On-site recreational opportunities with miles of pathways, a soccer field-sized park, tot lots, tennis courts, and the historic barn; a public transit stop located at the community's entrance.

- Architectural standards for designs that encourage the lasting values of the rural, Craftsman, and prairie styles; a stormwater management design that provides for on-site retention, evaporation, and percolation.

- The preservation of the existing wooded slopes, which are home to many specimen oak trees and provide excellent wildlife habitat.

The open space owned by the community association and Robert Engstrom Companies is permanently guaranteed by a conservation easement granted to the Minnesota Land Trust. The easement provides both the municipality of Lake Elmo and The Fields' home owners with the perpetual protection of open space that they desired.

While the statewide Minnesota Land Trust is well funded and has an endowment for continued operations, it is nonetheless important to ensure that all documentation associated with a conservation easement provides for possible successor entities, particularly when a newly formed local land trust is the recipient of the easement.

Both the media's and the public's response to The Fields of St. Croix's environmental features has been overwhelming. According to Senn and Youngdahl, the primary home builder, potential home buyers have demonstrated a strong desire to be a part of a cohesive community that works with the natural environment.

In April 1998, Wyn John, the mayor of Lake Elmo, announced the Fields of St. Croix was the 1998 recipient of the Land Use and Community Development Award of the Minnesota Environmental Initiative (MEI). MEI promotes the continuous improvement and environmental performance of business, government, and advocacy organizations.

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## SMART GROWTH CASE STUDY: PRAIRIE CROSSING

Normal View

### A Green Building/Cluster Development Project

**Grayslake, Ill.**
*Prairie Crossing began as the dream of Gaylord and Dorothy Donnelly and other neighbors on the Liberty Prairie Reserve. They determined to build a community where people could enjoy the beautiful open landscape of Central Lake County, just as they did, and help to preserve it.*

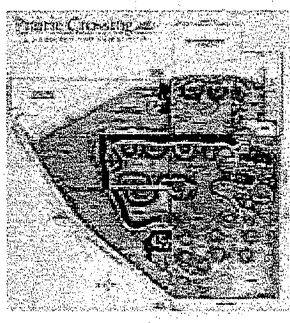
**Figures**

- 337 single-family homes on 667 acres
- 350 acres devoted to prairies, pastures, farms, fields, gardens, marshes and lakes

**Features**

- 50% energy-saving construction techniques and materials
- Community-supported organic garden

Prairie Crossing is dedicated to preserving the distinctive open landscape of central Lake County and encouraging daily living in harmony with the environment. The community is the western anchor of the Liberty Prairie Reserve, a 2,500-acre preserve of forest, marshes, prairies, and farmland



**The Homes**
Four different kinds of home sites are available at Prairie Crossing. Sixty Village home sites are located in a neo-traditional village which features a Market Square and Village Green. Prairie Crossing offers more than a dozen different home styles, in either the Settler or Homestead Series, that range in size from 1,140 square feet to 3,428 square feet, with 2 to 5 bedrooms, and in price from $239,900 to $427,900.

**Charter School**
Excellence in education is achieved by developing a strong bond between the school and the community. The Prairie Crossing Charter School blossomed forth in the midst of the Prairie Crossing Development. The Prairie Crossing Community is sharing many facilities with the school. It is important to instill respect for those facilities in all students and help students to find ways to give back generously to the neighborhood community. Students are also part of a much larger community. Each year the school is committed to either one long-term community project or several short-term ones.

Ten guiding principles serve as the foundation upon which decisions are made at Prairie Crossing:

1. Economic viability
2. Aesthetic design and high-quality construction
3. Lifelong learning and education

4. Energy conservation
5. Convenient and efficient transportation
6. Economic and racial diversity
7. A sense of community
8. A sense of place
9. A healthy lifestyle
10. Environmental protection and enhancement

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NATIONAL ASSOCIATION OF HOME BUILDERS

# SMART GROWTH CASE STUDY: ABRAHAM'S LANDING

Normal View

## A Green Building/Cluster Development Project

**St. David's, Pa.**

*This 13-acre custom-home project in St. David's, Pa. provides a good example of taking measures to handle storm water runoff in a sensitive manner in order to protect adjacent wetlands.*

Pohlig Builders of Malvern, Pa., sought approval to construct seven high-end custom homes on a former estate in a highly desirable residential area near the historic community of Radnor. The builder ran into substantial opposition from adjacent landowners who raised several concerns about the project.

Well regarded for developing environmentally sensitive custom-made home projects, Pohlig Builders agreed to respond to the landowners' concerns by taking special measures to protect a wetlands area on the site and a streamhead adjoining the property. Adopting a comprehensive approach to wetlands protection, the builder considered both the quantity and quality of the site's stormwater runoff in relation to the adjoining wetlands.

Further, Pohlig retained the services of the Philadelphia-based firm of Tourbier and Walmsley, an organization noted for its considerable experience in designing nonpoint source pollution abatement systems. Tourbier and Walmsley developed a vegetative filter strip for the area between the homes and the adjacent wetlands to purify the project's storm water runoff before it reaches the wetlands.

Vegetative filter strips use vegetable matter such as rough grasses and forest litter to remove solids suspended in storm water runoff, thereby preventing the solids from reaching water courses. The 150-foot-wide filter strip at Abraham's Lane includes three distinct elements: a dense, grassy primary filter constructed of a mix of hydroseeded grasses and planted perennial and ornamental grasses; an expansive section of trees, including downy shadblow, red maple, and willow oak, overplanted into the grasses with bare-root whip stock; and a rooted barrier of erosion-resistant woody shrubs to protect the bare-root whip stock until it becomes established. The filter strip was designed to grow over time into a wooded area that will enhance the site.

To ensure surface recharge of the fragile wetlands system with an appropriate water velocity, Toubier and Walmsley had to devise a method of managing storm water quantity. The consultants added a level spreader trench to the edge of the vegetative filter strip closest to the homes to alter the runoff from a concentrated to a sheet flow. Additional sediment and erosion control devices such as silt fences were deployed during active construction of the project. The total cost of all the nonpoint source pollution controls added $30,000 to the cost of the development.

Radnor Township, Pennsylvania

# Government

Welcome to Radnor!
Schools
Business & Shopping
Community Organizations

For Our Residents
For Potential Residents
Doing Business in Radnor

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What's New
Overview
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- Ezine
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- Voter Information
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Public Services
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- Public Works
- Engineering
- Parks & Recreation
- Animal Control

Community Development
- Growth & Development
- New Construction & Development
- Open Space Acquisition
- Zoning

## New Construction and Redevelopment

The Township has continued to experience sustained growth in the past decade. The number of building permits (for new construction or additions and accessories to existing structures) issued by the Township has increased gradually since 1990.

### New Construction and Redevelopment, 2000-2003

| Development | No. of Homes | Current Average Sale Price |
|---|---|---|
| Ardrossan Farm | 18 | $2,200,000 |
| Edenton | 18 | $750,000 |
| Maplewood Road | 15 | $350,000 |
| Birches | 11 | $600,000 |
| Van Lear's Run | 10 | $750,000 |
| Harford Estates | 10 | $700,000 |
| Abraham's Lane | 9 | $1,250,000 |
| Ithan Woods | 8 | $750,000 |
| Biddulph Road | 8 | $700,000 |
| Applegate | 8 | $400,000 |
| Sullivan | 7 | $400,000 |
| Villanova University (Dormitories) | 4 | $22,000,000 |
| Iven Woods | 3 | $875,000 |
| Wooten Road | 3 | $850,000 |
| Boxwood Road | 4 | $750,000 |
| Harrison Road | 3 | $850,000 |
| Cabrini College (Dorms & Sports Complex) | | $13,000,000 |
| Villanova University (Engineering & Science Buildings) | | $12,000,000 |
| Radnor Township School District (Elementary, Middle & High School) | | $5,270,000 |
| Eastern College (Dormitory) | | $4,000,000 |
| Wyeth-Ayerst | | $2,000,000 |
| Retail Office Building Lancaster Avenue | | $1,600,000 |
| Agnes Irwin School Addition | | $6,400,000 |
| Villanova University Monastery addition | | $3,325,000 |

Note: Figures listed for commercial and institutional properties denote estimated construction costs.

Construction codes, on which building in the Township is based, serve as a basis for conducting field inspections by department staff. Copies of the Township's building, plumbing, mechanical, fire prevention, electrical, and property maintenance codes and the fee schedule may be examined in the Community Development Department or at the Radnor Memorial Library.

- Design Review
- Health
- Property Maintenance
- Gateway Enhancement Strategy

Finance & Taxes
- Real Estate Tax
- Reassessment of Property Values
- Realty Transfer Tax
- Sewer
- Business Privilege
- Mercantile
- Emergency & Municipal Services Tax
- Amusement
- Request for Proposals

Welcome! | Community Calendar | New Additions
Government | Schools | Business & Shopping | Community Organizations | Other Government Sites

For Our Residents | For Potential Residents | Doing Business in Radnor | Employment

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PAST COMMUNITIES

**Applebrook**
Chester County
(9) New Custom Homes
(64) New Carriage Homes
Completed - 2004

**Greenwell Lane**
Radnor Township
(10) New Custom Homes
Completed - 2004

**Brooke Farm**
Radnor Township
Thirty Lot Site Development
(9) New Custom Homes
Completed - 2000

**Aisling**
Lower Merion Township
Seven Lot Site Development and
(6) New Custom Homes
Completed - 1999

**Brentford**
Tredyffrin Township
Eight Lot Site Development
(4) New Custom Homes
Completed - 1998

**Maple Hill**
Tredyffrin Township
20 Lot Site Development and
(4) New Custom Homes
Completed - 1998

**Abrahams Lane**
Radnor Township
Nine Lot Site Development and
(7) New Custom Homes
Completed - 1996

**Highcroft**
Willistown Township
Four Lot Site Development and
(3) New Custom Homes
Completed - 1996

**Bridlewood**
Lower Merion Township
Six Lot Site Development and
(3) New Custom Homes
Completed - 1995

**Sunwood Farm**
Schuykill Township
Ninety-Nine Lot Site Development and
(23) New Custom Homes
Completed - 1990

**Leopard Farm**
Easttown Township
(4) New Custom Homes
Completed - 1990

**North Valley Road**
Tredyffrin Township
(2) New Custom Homes
Completed - 1989

**Rock Creek Circle**
Easttown Township
Site Development and
(10) New Custom Homes
Completed - 1988

**Highland Avenue**
Easttown Township
(2) New Custom Homes
Completed - 1988

**Roberts Road**
Radnor Township
(3) New Custom Homes
Completed - 1987

**Paoli Executive Green**
Easttown Township
(2) 20,000 sq. ft. Office Buil
Completed - 1987

**The Enclave at Woodswo**
Radnor Township
Site Development and
(8) New Custom Homes
Completed - 1986

**Westwood**
West Goshen Township
(5) New Custom Homes
Completed - 1984

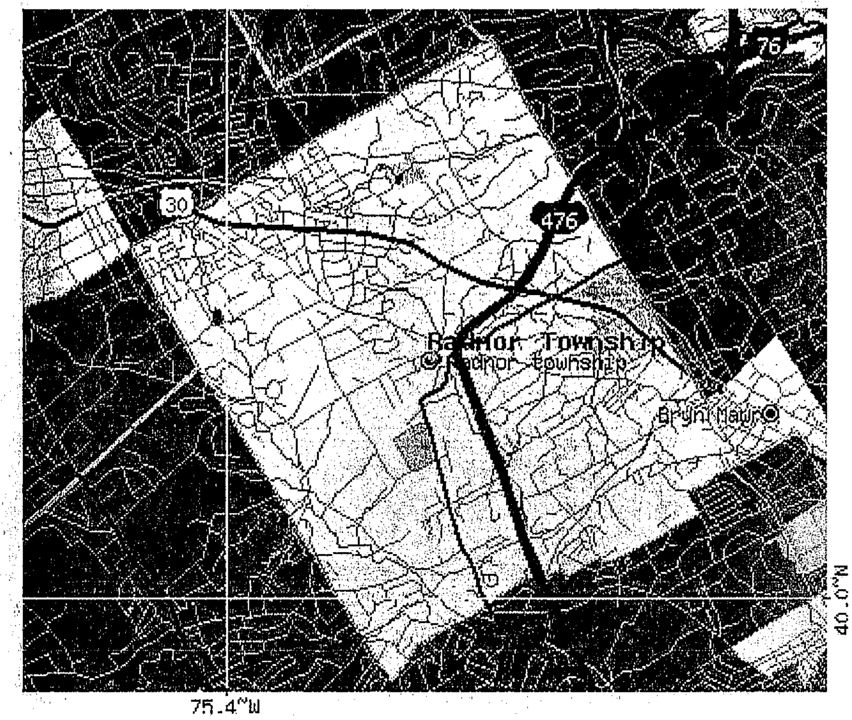
**West Wayne Avenue**
Radnor Township
Site Development and
(8) New Luxury Townhome
Completed - 1984

**Spring Valley Road**
East Whiteland Township
(5) New Custom Homes
Completed - 1982

# Radnor township, Delaware County, Pennsylvania (PA)



Back to: Delaware County, Pennsylvania (PA), All US cities.



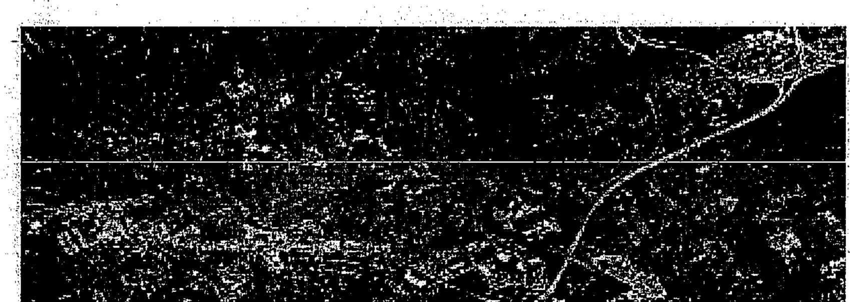

-Hispanic: 88.2%
- Black: 3.0%
- American Indian and Alaska Native: 0.1%
- Asian: 5.7%
- Native Hawaiian and Other Pacific Islander: 0.0%
- Hispanic or Latino: 2.0%
- Two or more races: 0.9%
- Some other race: 0.1%

Median age of males: 31.7
Median age of females: 33.5

Average houshold size: 2.39
Average family size: 3.08

Cities in this township include: Radnor Township.

Notable locations in this township outside city limits:



52% of Radnor township residents lived in the same house 5 years ago.
Out of people who lived in different houses, 24% lived in this county.
Out of people who lived in different counties, 42% lived in Pennsylvania.

Place of birth for U.S.-born residents:

- This state: 16170
- Northeast: 6518
- Midwest: 1892
- South: 2647
- West: 759

Median price asked for vacant for-sale houses in 2000: $425,000

Year house built:

- 1999 to March 2000: 35
- 1995 to 1998: 161
- 1990 to 1994: 226
- 1980 to 1989: 993
- 1970 to 1979: 1498
- 1960 to 1969: 1987
- 1950 to 1959: 2375
- 1940 to 1949: 969
- 1939 or earlier: 2487

Housing units in structures:

- One, detached: 5,842
- One, attached: 1,138
- Two: 179
- 3 or 4: 635
- 5 to 9: 361
- 10 to 19: 422
- 20 to 49: 482
- 50 or more: 1,667
- Boats, RVs, vans, etc.: 5

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Go back

The Basics

# House price appreciation by metro area

How does your city compare? Check out this list of 265 places and see which are hottest.

By MSN Money staff

Rankings for house-price appreciation from the Office of Federal Housing Enterprise Oversight (OFHEO) were released Dec. 1. Rankings are listed by Metropolitan Statistical Areas (MSAs); some MSAs have been further divided into Metropolitan Statistical Area Divisions (MSADs).

The Pacific Division, which comprises California, Oregon, Washington, Hawaii and Alaska, showed the largest house price increase over the last year: 17.3%.

The East North Central division, which comprises Ohio, Indiana, Illinois, Wisconsin and Michigan, saw the smallest annual house price increase: 5.7%.

Twenty-one of the 265 ranked areas had four-quarter appreciation exceeding 25%.

Overall, just 10 of the 265 ranked metropolitan areas experienced negative quarterly growth, compared with 15 in the last reporting cycle. No state or metropolitan area saw a decline over the past year.

Metropolitan areas in Arizona, California and Florida dominate the top 20 when ranked using annual price growth. For the first time since the fourth quarter of 2003, no Nevada metro areas ranked among the top 20. But two other Western states, Utah and Idaho, showed noticeable gains.

Metro areas in Indiana, Ohio and Texas saw the worst appreciation.

OFHEO's House Price Index is published on quarterly basis and tracks average house price changes in repeat sales or refinancings of the same single-family properties. OFHEO's index is based on analysis of data obtained from Fannie Mae and Freddie Mac from more than 30 million repeat transactions over the last 30 years.



Akron, OH thru Los Angeles | Louisville, KY through Yuba City, CA
Return to "The nation's hottest housing markets"

**Housing appreciation (in percent) by metro area***

| Metro area | Ranking* | 1-year | 3rd qtr. | 5-year |
|---|---|---|---|---|
| Akron, OH | 218 | 4.57 | 1.23 | 21.02 |
| Albany-Schenectady-Troy, NY | 69 | 14.98 | 3.91 | 68.25 |
| Albuquerque, NM | 79 | 13.66 | 4 | 37.36 |
| Allentown-Bethlehem-Easton, PA-NJ | 76 | 14.1 | 2.83 | 60.91 |

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| | | | | |
|---|---|---|---|---|
| Amarillo, TX | 179 | 6.12 | 2.44 | 22.51 |
| Anchorage, AK | 84 | 12.68 | 4.16 | 51.37 |
| Anderson, IN | 260 | 2.62 | 2.86 | 18.17 |
| Anderson, SC | 178 | 6.14 | 2.59 | 22.79 |
| Ann Arbor, MI | 245 | 3.91 | -0.25 | 27.59 |
| Appleton, WI | 240 | 4.05 | 0.9 | 25.19 |
| Asheville, NC | 129 | 8.38 | 1.62 | 41.35 |
| Athens-Clarke County, GA | 233 | 4.25 | 0.37 | 29.22 |
| Atlanta-Sandy Springs-Marietta, GA | 196 | 5.36 | 1.39 | 27.93 |
| Atlantic City, NJ | 52 | 17.59 | 2.18 | 91.92 |
| Augusta-Richmond County, GA-SC | 127 | 8.42 | 1.43 | 29.62 |
| Austin-Round Rock, TX | 174 | 6.48 | 1.94 | 18.64 |
| Bakersfield, CA | 13 | 27.07 | 6.27 | 123.68 |
| Baltimore-Towson, MD | 43 | 19.05 | 4.25 | 89.14 |
| Barnstable Town, MA | 107 | 9.79 | 1.52 | 91.15 |
| Baton Rouge, LA | 216 | 4.62 | 0.92 | 22.22 |
| Battle Creek, MI | 223 | 4.52 | 2.37 | 24.53 |
| Bay City, MI | 168 | 6.69 | 0.98 | 25.09 |
| Beaumont-Port Arthur, TX | 262 | 2.43 | -0.38 | 21.29 |
| Bellingham, WA | 39 | 19.96 | 3.69 | 75.98 |
| Bend, OR | 34 | 21.24 | 7.62 | 66.15 |
| Bethesda-Frederick-Gaithersburg, MD (MSAD) | 47 | 18 | 3.58 | 101.56 |
| Billings, MT | 99 | 10.4 | 1.08 | 43.52 |
| Birmingham-Hoover, AL | 121 | 8.66 | 1.91 | 31.9 |
| Blacksburg-Christiansburg-Radford, VA | 113 | 9.33 | 0.96 | 39.37 |
| Bloomington, IN | 141 | 7.63 | 1.58 | 28.63 |
| Bloomington-Normal, IL | 252 | 3.51 | -0.13 | 18.25 |
| Boise City-Nampa, ID | 74 | 14.29 | 6.28 | 39.71 |
| Boston-Quincy, MA (MSAD) | 152 | 7.17 | 0.93 | 69.61 |
| Boulder, CO | 182 | 5.96 | 1.77 | 26.37 |
| Bowling Green, KY | 137 | 7.84 | 3 | 23.57 |
| Bremerton-Silverdale, WA | 50 | 17.71 | 5.07 | 65.35 |
| Bridgeport-Stamford-Norwalk, CT | 101 | 10.3 | 1.51 | 65.91 |
| Buffalo-Niagara Falls, NY | 184 | 5.89 | 2.45 | 29.83 |
| Burlington, NC | 251 | 3.57 | -1.24 | 13.47 |
| Burlington-South Burlington, VT | 91 | 11.87 | 3.51 | 62.02 |
| Cambridge-Newton-Framingham, MA (MSAD) | 146 | 7.39 | 1.22 | 56.18 |
| Camden, NJ (MSAD) | 72 | 14.51 | 3.55 | 78.25 |
| Canton-Massillon, OH | 244 | 3.95 | 1.17 | 21.61 |
| Cape Coral-Fort Myers, FL | 2 | 33.16 | 7.86 | 119.85 |
| Cedar Rapids, IA | 253 | 3.44 | 0.4 | 20.12 |
| Champaign-Urbana, IL | 133 | 8.24 | 3.34 | 33.98 |
| Charleston, WV | 188 | 5.66 | 1.25 | 20.99 |
| Charleston-North Charleston, SC | 66 | 15.61 | 4.06 | 51.46 |
| Charlotte-Gastonia-Concord, NC-SC | 222 | 4.52 | 1.16 | 18.98 |
| Charlottesville, VA | 63 | 15.86 | 2.66 | 71.78 |
| Chattanooga, TN-GA | 163 | 6.92 | 0.95 | 31.93 |
| Cheyenne, WY | 125 | 8.53 | 3.45 | 44.29 |

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|---|---|---|---|---|
| Chicago-Naperville-Joliet, IL (MSAD) | 118 | 9.05 | 2.05 | 47.71 |
| Chico, CA | 42 | 19.23 | 4.62 | 117.14 |
| Cincinnati-Middletown, OH-KY-IN | 208 | 4.85 | 1.16 | 23.7 |
| Cleveland-Elyria-Mentor, OH | 239 | 4.08 | 0.84 | 22.35 |
| Coeur d'Alene, ID | 7 | 29.88 | 6.32 | 69 |
| Colorado Springs, CO | 161 | 7 | 1.23 | 32.54 |
| Columbia, MO | 139 | 7.8 | 3.15 | 28.2 |
| Columbia, SC | 151 | 7.26 | 1.52 | 27.88 |
| Columbus, GA-AL | 112 | 9.39 | 3.38 | 33.28 |
| Columbus, IN | 186 | 5.8 | 2.03 | 17.6 |
| Columbus, OH | 210 | 4.79 | 0.91 | 24.46 |
| Dallas-Plano-Irving, TX (MSAD) | 236 | 4.18 | 0.64 | 20.99 |
| Davenport-Moline-Rock Island, IA-IL | 204 | 4.94 | 1.93 | 25.51 |
| Dayton, OH | 242 | 3.99 | 0.97 | 19.35 |
| Deltona-Daytona Beach-Ormond Beach, FL | 16 | 26.61 | 6.19 | 101.69 |
| Denver-Aurora, CO | 238 | 4.11 | 0.76 | 26.55 |
| Des Moines, IA | 180 | 6.11 | 1.55 | 27.92 |
| Detroit-Livonia-Dearborn, MI (MSAD) | 261 | 2.48 | -0.12 | 22.1 |
| Dubuque, IA | 194 | 5.51 | 2.44 | 27.6 |
| Duluth, MN-WI | 147 | 7.36 | 0.92 | 56.8 |
| Durham, NC | 193 | 5.51 | 0.86 | 23.38 |
| Eau Claire, WI | 153 | 7.13 | 3.05 | 34 |
| Edison, NJ (MSAD) | 80 | 13.58 | 3.15 | 89.29 |
| El Paso, TX | 131 | 8.35 | 2.74 | 30.55 |
| Elkhart-Goshen, IN | 173 | 6.5 | 3.17 | 20.92 |
| Essex County, MA (MSAD) | 162 | 6.95 | 1.32 | 62.27 |
| Eugene-Springfield, OR | 58 | 16.55 | 4.75 | 46.71 |
| Evansville, IN-KY | 234 | 4.21 | 1.1 | 21.07 |
| Fargo, ND-MN | 170 | 6.63 | 0.74 | 39.67 |
| Fayetteville-Springdale-Rogers, AR-MO | 90 | 11.97 | 3.18 | 43.81 |
| Flagstaff, AZ-UT | 27 | 22.76 | 6.96 | 76.54 |
| Flint, MI | 225 | 4.5 | 1.55 | 23.25 |
| Florence, SC | 231 | 4.34 | 1.4 | 24.04 |
| Fond du Lac, WI | 181 | 6.05 | 1.35 | 25.2 |
| Fort Collins-Loveland, CO | 241 | 4.03 | 0.99 | 28.83 |
| Fort Lauderdale-Pompano Beach-Deerfield Beach, FL (MSAD) | 18 | 26.55 | 6.49 | 125.67 |
| Fort Wayne, IN | 229 | 4.4 | 1.72 | 17.09 |
| Fort Worth-Arlington, TX (MSAD) | 246 | 3.87 | 1.14 | 21.31 |
| Fresno, CA | 26 | 23.36 | 5.14 | 134 |
| Gainesville, GA | 190 | 5.62 | 3.1 | 28.21 |
| Gary, IN (MSAD) | 169 | 6.64 | 1.67 | 24.35 |
| Grand Junction, CO | 104 | 10.04 | 3.98 | 44.82 |
| Grand Rapids-Wyoming, MI | 206 | 4.88 | 0.95 | 24.44 |
| Greeley, CO | 264 | 2.21 | -0.72 | 25.55 |
| Green Bay, WI | 212 | 4.71 | 0.74 | 27.33 |
| Greensboro-High Point, NC | 215 | 4.65 | 1.88 | 18.55 |
| Greenville, SC | 209 | 4.8 | 1.29 | 21.81 |
| Gulfport-Biloxi, MS | 102 | 10.14 | 2.83 | 27.61 |

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| | | | | |
|---|---|---|---|---|
| Hagerstown-Martinsburg, MD-WV | 32 | 21.84 | 4.91 | 82.06 |
| Harrisburg-Carlisle, PA | 111 | 9.52 | 2.52 | 34.83 |
| Hartford-West Hartford-East Hartford, CT | 106 | 10 | 2.63 | 55.99 |
| Hickory-Lenoir-Morganton, NC | 226 | 4.48 | 1.64 | 19.32 |
| Holland-Grand Haven, MI | 203 | 5 | 1.15 | 23.28 |
| Honolulu, HI | 28 | 22.45 | 6.21 | 93.5 |
| Houston-Baytown-Sugar Land, TX | 220 | 4.55 | 1.17 | 25.16 |
| Huntsville, AL | 158 | 7.02 | 3.1 | 24.36 |
| Indianapolis, IN | 214 | 4.66 | 1.21 | 20.42 |
| Iowa City, IA | 165 | 6.83 | 2.41 | 28.06 |
| Jackson, MI | 259 | 2.76 | -1.16 | 26.43 |
| Jackson, MS | 164 | 6.88 | 2.09 | 25.13 |
| Jacksonville, FL | 45 | 18.51 | 4.03 | 71.78 |
| Janesville, WI | 171 | 6.62 | 1.04 | 27.16 |
| Jefferson City, MO | 248 | 3.81 | 1.1 | 21.71 |
| Joplin, MO | 243 | 3.97 | 2.1 | 27.06 |
| Kalamazoo-Portage, MI | 205 | 4.89 | 1.43 | 25.51 |
| Kankakee-Bradley, IL | 135 | 8.07 | 2.28 | 26.74 |
| Kansas City, MO-KS | 202 | 5.13 | 1.35 | 29.41 |
| Kennewick-Richland-Pasco, WA | 256 | 3.16 | 0.15 | 27.15 |
| Kingsport-Bristol-Bristol, TN-VA | 172 | 6.55 | 0.25 | 29.71 |
| Knoxville, TN | 114 | 9.15 | 3.27 | 33.79 |
| Kokomo, IN | 224 | 4.51 | 1.79 | 14.88 |
| La Crosse, WI-MN | 157 | 7.06 | 2.64 | 33.41 |
| Lafayette, IN | 263 | 2.25 | 0.86 | 10.7 |
| Lafayette, LA | 156 | 7.09 | 1.72 | 29.77 |
| Lake County-Kenosha County, IL-WI (MSAD) | 166 | 6.75 | 1.23 | 38.87 |
| Lakeland, FL | 19 | 26.02 | 9.34 | 70.76 |
| Lancaster, PA | 100 | 10.36 | 2.79 | 42.58 |
| Lansing-East Lansing, MI | 255 | 3.26 | 0.86 | 29.25 |
| Las Vegas-Paradise, NV | 77 | 13.77 | 2.26 | 99.04 |
| Lawrence, KS | 160 | 7.01 | 0.26 | 33.57 |
| Lexington-Fayette, KY | 183 | 5.92 | 1.63 | 27.93 |
| Lima, OH | 189 | 5.65 | 2.18 | 24.67 |
| Lincoln, NE | 197 | 5.35 | 1.07 | 22.63 |
| Little Rock-North Little Rock, AR | 167 | 6.7 | 1.51 | 27.46 |
| Logan, UT-ID | 115 | 9.1 | 2.39 | 21.93 |
| Longview, WA | 82 | 12.89 | 4.69 | 30.54 |
| Los Angeles-Long Beach-Glendale, CA (MSAD) | 44 | 18.81 | 4.6 | 121.59 |

* Note: Rankings based on annual percentage change, for all MSAs containing at least 15,000 transactions over the last 10 years.

Akron, OH thru Los Angeles | Louisville, KY through Yuba City, CA

**Return to "The nation's hottest housing markets"**

A005328

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- Investing 101: How to buy your first stock
- BusinessWeek: France kicks the habit
- Forbes: The world's best-paid supermodels
- $1-a-year CEOs doing fine, thanks

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General Information

## Housing statistics

## San Diego's housing crisis – statistics and quotes

**Increasing housing prices vs. incomes in San Diego:**

- San Diego County's high housing prices, coupled with its relatively low wages, make it the second least affordable area in the country. (National Association of Home Builders, 2005)

- The average **new** detached home in San Diego County sells for $861,265 – a 350 percent increase over 1996 ($245,884). (*The Daily Transcript*/MarketPointe Realty 10/21/05)

- Meanwhile, in the past six years, the median household income in San Diego increased only 21 percent for a family of four. (*San Diego Union Tribune,* 7/10/05)

- The median price for **existing** houses for October 2005 was $560,000 (as compared to a national median price of $225,000). The median price for resale condos for that period was $398,250. (*San Diego Union-Tribune*/DataQuick Information Systems, 11/12/05 and *The Daily Transcript*, 8/9/05)

- "To afford a median-priced home today in San Diego, a household would need an annual income of nearly $110,000..." [versus the median $63,400 for a family of four, as per the U.S. Department of Housing and Urban Development]. That assumes a 10 percent down payment and a 30-year fixed-rate financing at current prices." (SDUT, 7/10/05)

- The San Diego Association of Governments estimates that 172,000 local employees, or 13 percent of the work force, earn less than $8.35 an hour.

- According to the Federal Bureau of Labor Statistics, in the past year, San Diego lost 15 percent of its manufacturing jobs (which are typically higher wage than retail and hospitality jobs).(*SDBJ*, 6/27/05)

- Examples of average wages not keeping up with housing prices (according to the National Housing Conference's Center for Housing Policy): elementary school teacher, $48,840; police officer, $58,370; nurse $35,080; retail salesperson, $19,150; and janitor, $18,110. (San Diego Housing Federation weekly brief, 8/27/04)

**Attitudes about Housing:**

- According to a Public Policy Institute of California survey: "The cost of housing is one of the biggest issues on the minds of California residents. More residents (55 percent) see the lack of affordable housing as a bigger issue than population growth (35 percent), lack of well-paying jobs (35 percent), or air pollution (30 percent)." (*The Daily Transcript*, 6/1/05)

**Housing Price Impacts on Employment:**

- "'San Diego's Housing Market is one of the most inflated in the country – a detrimental factor in terms of recruiting and retaining employees,' said Kristine Norquist, Communications Manager for the San Diego Regional Chamber of Commerce." (*The Daily Transcript*, 2/18/05)
- "Corporate relocation specialists say the area's high costs are making it increasingly hard to find newcomers to replace the companies that are departing." (*SDUT*, 6/12/05)
- "We've dropped out of the top 20 on *Forbes Magazine's* ranking of the 'Best Places for Business and Careers.' ... The primary factors: cost of living (we're sixth costliest out of 150) and cost of doing business (we're third costliest out of 150)." (Tom Blair, i on San Diego/*San Diego Magazine* July 2005)
- In San Diego, 29 percent of residents are considering moving out of the state because of high housing prices, according to the Public Policy Institute of California. (*SDUT*, 11/18/04)
- "For the first time in nearly a decade, more people moved out of San Diego County last year than moved here from other U.S. locales – and economists say the trend could continue as local workers find it harder to cope with stagnant salaries, a high cost of living and skyrocketing home prices." (*SDUT*, 6/12/05)

**Condo conversions:**

- "Condo conversions are one of the hottest topics in real estate right now, with supporters touting them as a ready source of affordable housing and critics warning that they are reducing the supply of rental units for low-income families in the San Diego market." (*SDBJ*, 7/18/05)
- "Converted units may be an affordable alternative for many, but the price hasn't exactly been standing still. In fact, the price in that segment has climbed by 42 percent during the past 24 months. Condominium conversions account for about 51 percent of the new attached market." (The *Daily Transcript*/MarketPointe Realty Advisors, 4/21/05)

**Apartment shortages and rents in San Diego:**

- The average apartment rent in San Diego is $1,236 – a nearly 100 percent increase from 1990, when average rents were $643 (*The Daily Transcript*/Associated Press 7/21/05)
- "Nearly all the apartment units being constructed are in the luxury category... In fact, units built since 1998 are averaging $1,581 per month, compared to $1,091 [for] units built prior to 1998, reflecting a 45 percent premium for newer units." (*The Daily Transcript* /MarketPoint Realty Advisors 3/28/05)
- Rental vacancies in San Diego have fluctuated between less than one and four percent from 1997-2005. The region's vacancy rate is currently 3.9

percent. (San Diego County Apartment Association Spring 2005 Vacancy and Rental Rate Survey)

- The national apartment vacancy rate is currently at nine percent. (*The Daily Transcript*, 8/25/05)

**Housing policy and trends**

- "Inclusionary zoning has surfaced as one policy solution to rising housing costs in big cities...San Diego is a "trail-blazing example that other urban centers can follow." (American Planners Association, *Zoning Practice*, October 2004)

- "The [San Diego] region has effectively made a big investment in 'low-value-added jobs' through its support of tourism and now faces problems with a populace increasingly unable to afford housing in the area," said Marney Cox, lead economist for the San Diego Association of Governments. (*SDUT*, 8/30/05)

- Imperial Valley: "Developments are exploding all over the Imperial Valley, and homebuyers and developers of all kinds don't seem to mind the heat...'It's the only affordable market left for Southern California,' said John Trotter of Capstone Advisors. 'People are moving east to buy homes in Imperial County, and it's going to continue to grow because of affordable housing,' said Mitch Mitchell of the San Diego Chamber of Commerce. The average price of a new single-family detached home...in Imperial Valley is $293,707." (*The Daily Transcript*, 5/23/05)

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# [*PG437]*EQUITY IN EDEN: CAN ENVIRONMENTAL PROTECTION AND AFFORDABLE HOUSING COMFORTABLY COHABIT IN SUBURBIA?*

RUSTY RUSSELL*

*Abstract:* State-based affordable housing initiatives have survived decades of controversy. Two of the most successful—in Massachusetts and New Jersey—encourage homebuilders to bypass local regulations when zoning ordinances limit available land. Opponents assert that these programs invite developers to pillage open space, impairing wetlands and promoting sprawl. This Article examines the low- and moderate-income housing programs established by the so-called "Anti-Snob Zoning Act" in Massachusetts and the *Mount Laurel* doctrine in New Jersey. Drawing on Oregon's integrated planning regime as a point of contrast, it analyzes the potential for tension between policies that advance affordable housing in the suburbs and the asserted municipal interest in safeguarding the local environment. Finding that elements of the legal and regulatory structure appear to promote this conflict, the Article concludes with the observation that a more coherent statewide planning system could better integrate affordable housing and the environment, and offers thoughts on how to alter the perception that the two are adversaries.

## INTRODUCTION

This Article examines the potential for conflict—and congruence—between the benchmark state efforts of Massachusetts and New Jersey to site affordable housing in municipalities that historically have opposed it, and initiatives by communities and their citizens to [*PG438]protect the local environment. When not pretextual, such initiatives seek to address the health and safety impacts of disaggregated living patterns, consumption of open space, short- and long-term harm to ecosystems, and loss of biodiversity. The State of Oregon's land use planning system serves as a point of contrast, and accusation.

## *I.* THE EQUITY DIMENSION

Policies favoring environmental protection and affordable housing are sometimes said to conflict because they embody differing perspectives on the principle of equity.[1] Environmentalism tends to focus on intergenerational distribution—equity over the long term. A fundamental concern is the extent to which the present generation can defer the costs of its activities.[2] Affordable housing policy, conversely, concentrates more intensely on existing inequalities. These include disparities in available resources for shelter, as well as the ability of local government to supply services such as education, fire and police protection, and public works. Considerations of intergenerational equity frequently yield to more immediate demands.[3] Institutional [*PG439]remedies supported by housing advocates appear to favor housing over the environment,[4] despite repeated expressions of concern for the latter. But the relationship between the two is more complex. Feigned environmentalism may not save any trees, yet it may be decisive in obstructing low-cost housing.[5]

Another major source of tension is governmental. It surfaces when a decision to promote affordable housing, usually made at the state level, collides with local financial needs and political limitations. Under the authority typically delegated by state constitutions, municipalities can and do provide a wide range of public services.[6] In the usual case, a sizable percentage of the local budget must be raised through property assessments,[7] and K–12 education can easily consume half of it or more.[8] A direct relationship exists between the level and quality of municipal services, and the structure of local zoning regulations.[9]

As a result of this interplay, current residents of a given community work hard to maximize their own economic prospects.[10] By deciding what package of services to offer and how to cultivate the most robust tax base to pay for it, munities exercise powers delegated by the state legislature to shift as much of their costs as possible onto the citizens ther towns and cities.[11] This permutation of the famil[*PG440]iar "tragedy of the commons"[12] ensures that many municipalities will "over produce" land that is off-limits to low-cost housing. This objective may be advanced by a variety of antiquated zoning and land use practices that inhibit the transition to a more diverse and affordable housing stock.[13]

A strain of local environmentalism animated by variations on the NIMBY theme can add to this tension.[14] The problem arises when local environmental solicitude serves as camouflage for less wholesome agendas.[15] Intentionally, or by indirection, existing residents seek to maximize their net benefits by pursuing strategies that limit or eliminate affordable ..sing, particularly housing for growing families. The cost of municipal services that these residents demand may exc .r property tax allotment, whether paid directly or through rent. Education costs incurred by families will nearly alwa.. exceed tax receipts, unless the family owns an expensive home.[16]

Given these conditions, the meaning of environmental protection takes on increasing subjectivity.[17] To housing advocates and those who seek affordable shelter in suburban communities, saving the local environment may serve as code for exclusionary zoning[18] and all it conceals.[19] To those who seek to protect the environment, an aggres[*PG441]sive affordable housing policy may be received as the lumbering intervention of a distant and ill-informed regulatory state.[20]

This Article extensively analyzes the Massachusetts and New Jersey approaches to affordable housing and then compares these approaches with Oregon's system. The first two are widely considered to be the pathbreaking affordable housing initiatives in the nation. The third incorporates housing into a much broader set of planning goals. The Massachusetts and New Jersey programs parallel one another. The Oregon system significantly differs. Together they illustrate the range of strategies attempted with some success so far. This Article examines each of these approaches for evidence that, in intent, structure, or result, a particular approach may cause conflict between legitimate local environmental programs and the more equitable distribution of housing. To accomplish this task, it is necessary to investigate the relationship among local governmental structure, local and regional environmental quality, and affordable housing policy.

## *II.* Local Environmental Concerns

Degradation of air, water, and land—the fundamental elements of an ecosystem—eventually harms almost all living things and every human community. Impacts big and small spill with abandon across political boundaries of all dimensions.[21] Yet, i.. the end, their effects are felt locally. Unfortunately, cities, towns, and myriad other municipal divisions may not offer a ..d platform from which to address environmental risk.[22]

Some threats are addressed primarily at the national level, although several major environmental laws delegate significant responsibility to the states, allowing them to impose stricter environmental standards.[23] Through state delegation, this cooperative federalism extends to municipalities, which typically enjoy broad latitude in ad[*PG442]dressing matters of local concern.[24] As a result of this delegated authority, cities and towns may adopt additional controls, especially those that address particular sensitivities.[25]

This might be sufficient to protect the environment if the federal environmental statutes achieved their objectives. But they often cannot.[26] A significant reason is that these laws, along with their many state counterparts, do not adequately address the expansion of existing environmental risk or new risk,[27] and they do not specify a defensible level of risk reduction.[28]

[*PG443] One of the major drivers—arguably, *the* major driver—of environmental risk is intensifying human occupation of the 2.7 billion-acre land area[29] of the United States.[30] When that growth is unplanned, or poses untoward environmental risk, it is commonly referred to as "sprawl." The definition of sprawl, like its essence, is nebulous.[31] Nonetheless, its impacts are widely acknowledged, and include: (1) a preference for the consumption of undeveloped "greenfields";[32] (2) scattered, "leapfrog," strip, or low-density development;[33] (3) housing that delivers a great deal of personal space to meet the demands of individuals or individual nuclear families;[34] (4) employment patterns calling for lengthy commutes;[35] (5) economic conditions requiring more household members to be employed outside the home and, as a result, more automobiles and driving per household;[36] (6) increased segregation of land uses, which cuts residential areas off from the loci of consumption and employment; and (7) development that does not relate to its surroundings, ..r in use, size, structure, or appearance.[37]

Sprawl is a dynamic that favors chaotic patterns of growth and reinforces environmental risk. That risk comes in all sizes—some is exceedingly local, some widespread. By definition, out-of-control development consumes land unwisely. Too much undeveloped acreage is taken, and it is taken too quickly. Sprawl development ignores potential sites in more built-up areas in favor of the lower prices of exurban greenfields.[38] Even with an exaction aimed at compensating [*PG444]local government for the required infrastructure, much of the externalized costs will continue to be borne by the wider community.[39]

..e environmental impact of sprawl arises from two mutually reinforcing phenomena: (1) inefficient use of land[40] and (2) a significant disconnect between the political jurisdiction having control over key land use decisions, and the jurisdictions that must bear the negative consequences of those decisions.[41] In the face of wasteful demand, many municipalities under price inputs (undeveloped land and services), and thus create an incentive to use those inputs at an inefficiently high level. But because others elsewhere pay part of their cost, the municipality has little reason to desist. The incentive to do so is further reduced because most of the benefits of the development remain local.[42] Those burdened by the impacts will find objection difficult, facing significant costs just to discover they are victims, and even more to organize a legal or political response.[43] It may simply be impossible to challenge such local actions successfully.

It is also well settled that cities and towns have an incentive to encourage certain types of development, and to discourage others.[44] Because they are small, compete with many other political subdivisions, and enjoy the benefit of customized legal tools, these communities often find it easier to avoid what they perceive is bad than to entice the good.[45]

[*PG445] Desirable development earns a positive fiscal dividend[46]—that is, it returns more in local taxes than it consumes in municipal services. Commercial development of all types generally qualifies, as does a narrow spectrum of residential uses, including housing for the elderly,[47] units restricted to one or two bedrooms, and expensive single-family homes. The latter, due in part to efficiency and in part to demand, tend to be sited on large lots in large subdivisions. The ideal conditions for development of this type often are found in natural areas, lying far from employment, education, and urban centers.[48]

The result is environmental degradation. Its impacts are widespread and difficult to trace, and do not easily lend themselves to effective local regulation. Even assuming that preemption is not an obstacle, often the most that a ...munity can do to address it is to impose high costs on its residents and voters in exchange for a range of benefits that are far more broadly distributed, both in distance and in time. Needless to say, regulatory initiatives of this type do not receive a high priority. Typically, a homeowner's most valuable asset is his or her home[49] and any threat to that asset's value will be stoutly resisted.[50]

Despite this, the myriad impacts of sprawl are well documented and growing.[51] Decreases in population density have greatly out[*PG446]stripped population growth over the past five decades.[52] The trend has been particularly dramatic in urbanized areas. In Massachusetts, for instance, developed land area expanded at a rate more than six times higher than the rate of population growth.[53] At the national level, the trend has been similar, if not as pronounced.[54] Demographics and employment are mutually reinforcing. The data show that as the suburban population has increased, so have the number of suburban jobs.[55]

The effects of sprawl also must be considered in connection with tasks that municipal governments typically undertake. These include the provision of local services, zoning and land use planning,[56] and revenue collection.

[*PG447] As unplanned and premature development, sprawl results in a host of environmental insults. Its effects range from the highly-localized to small but significant contributions to major national and international concerns. Sprawl is at least partially responsible for increases in:

(1) Air pollution and climate change emissions[57] resulting from the purchase and excessive use of fuel-inefficient vehicles by relatively affluent suburbanites;
(2) nonpoint source pollution of water bodies, caused by runoff from paved areas, as well as infiltration from faulty or under-regulated septic systems;[58]
(3) loss of wetlands[59] and open space;[60]
(4) ecosystem fragmentation, and the resultant loss of habitat and species;[61] and
(5) inefficient consumption driven by non-renewable, limited, and polluting inputs, such as water,[62] electricity, and on-site fossil fuels like natural gas, heating oil, and propane.[63]

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To address sprawl, the environmental and planning community[64] has lately focussed on "smart growth," the subject of numerous recent political initiatives.[65] Smart growth, although fuzzy around the [*PG448]edges,[66] generally straddles the boundary between the reactive and the innovative. Smart growth planning retrospectively attempts to correct years of ıwl-inducing policies, including *Euclid*-inspired zoning;[67] the over-reliance on local governments to regulate development and land use; and suburb-[68] and automobile-oriented governmental subsidies.[69] It also looks forward, opening a broad tent to new ideas that promise to be environmentally benign, as well as equitable and aesthetically pleasing.[70]

### *III.* Affordable Housing: Background

Sprawl may be the primary force behind environmental degradation in suburbia, but to what extent does affordable housing policy intensify diffuse, inefficient patterns of development? That question must be addressed within the broader context of the rise of American suburbanization and powerful government policies that have supported and reinforced it for decades.

The suburban ideal has deep roots.[71] For at least two centuries, "the easy availability of housing and land has distinguished the United States from other nations of the world."[72] Over that time, frontier ideology of a particularly American character sharpened into a distaste [*PG449]for urban life, and reinforced a "drift . . . toward the periphery."[73] Over time, this grew into an "affinity for a detached home on a private lot [providing] the psychic value of privacy or castlehood."[74] Government policy responded to and intensified this migration. Between the mid-1930s and mid-1970s, for example, the Federal Housing Administration issued $119 billion worth of mortgage insurance, directly abetting the spreading carpet of suburbia.[75] Even without the strong hand of the federal government, the "national distrust of urban life and communal living"[76] ensured that residential diffusion would continue. Yet that hand repeatedly did intervene, and, in some cases, ensured that the only private housing the average middle-class family could afford was a suburban tract home.[77] As historian Kenneth Jackson noted, "[T]here were two necessary conditions for American residential deconcentration—the suburban ideal and population growth—and two fundamental causes—racial prejudice and cheap housing."[78] ernment responded to these conditions in a manner that reinforced their causes.[79]

[*PG450] Homeownership remains a central feature of the American Dream. It also presents a central policy challenge. The challenge arose directly from the suburbanization that started in the early part of the century and accelerated significantly as a result of government assistance after the Second World War.[80]

The fragmentation of the suburbs, from the central city and from each other, has contributed to the continuing perception that the supply of housing cannot meet perceived and projected demand.[81] This affordable housing "crisis"[82] is rendered more acute by the problem of diffusion—a problem that is worse for some communities than others.

Suburbs were developed as a haven for the middle- and upper-middle classes. Today, more people live there than in either cities or rural areas.[83] Although government policy after 1945 opened up these areas to a wider segment of the populace, that slice remained almost exclusively white and relatively affluent.[84] Suburban municipalities perpetuated this imbalance by exercising zoning and other regulatory power in a manner that tended to increase the price of land and thus the price of housing. Economically rational cities and towns possessed a strong interest in attracting residents and businesses that could pay their own way, and fending off those that could not.[85] Small governmental units arose on the currents of population, and state law evolved to facilitate suburban incorporation and protect new municipalities from annexation.[86] These two forces helped to infuse communities with a strong self-interest in their own brand of uniformity.[87] [*PG451] Ultimately, the widespread fragmentation of local government yielded high levels of suburban segregation.[88]

These complex changes have generated continuing, intense concern about affordable housing. It embodies several discrete issues. They include: (1) inadequate shelter in the core of many urban areas;[89] (2) lack of racial and ethnic rsity; (3) a wide gap between the location of affordable housing and the workplace; (4) barriers confronting middle-class families who seek to relocate to more affluent suburbs; (5) obstacles preventing the elderly from remaining in thei home communities; and (6) the overall lack of housing options that lie within the economic reach of lower-income groups.[90]

## IV. State Programs: Massachusetts, New Jersey, and Oregon

The question posed by this analysis is whether, and to what extent, three key approaches to affordable housing affect the ...l environment, for good or ill. These are the affordable housing programs developed in Massachusetts, New Jersey, ...d Oregon. Each State has followed a different path. In 1969, Massachusetts implemented an administrative process through the Massachusetts Low and Moderate Income Housing Act,[91] often called the "Anti-Snob Zoning Act," the "Comprehensive Permit Law," or just "40B." New Jersey's approach was announced by the state supreme court in a series of decisions arising out of the *Mount Laurel* litigation.[92] It rests on state constitutional principles.[93] Oregon's system is part of a broader statewide land use [*PG452]program designed to direct growth and housing to identified areas in or near urban centers.[94]

The earliest of these efforts, the Massachusetts program, offers builders a waiver of most local land use restrictions if they agree to construct housing that meets low- and moderate-income guidelines.[95] The New Jersey approach, announced in 1975 and converted into an administrative process a decade later, attempts more directly to identify local and regional need for affordable housing, and permits builders to sue municipalities that fail to establish a state-certified program to meet that need.[96] Oregon's approach, which differs significantly from the others, addresses housing in the context of nineteen statewide planning goals. These goals must be achieved by each county and by the Portland metropolitan area, or the communities risk losing state aid.[97]

### A. *The Massachusetts Comprehensive Permit Law: A Bright Line Test*

The Massachusetts program, though no stranger to controversy,[98] offers the virtue of simplicity. This is achieved through a combination of bright-line triggers and a passive approach that requires a relatively modest level of administrative oversight.

...e Comprehensive Permit Law empowers public or specified private developers to site qualifying low- and moderate-...ome housing[99] without regard to zoning restrictions, or other local land use [*PG453]regulations, in any city or town where less than 10% of the housing stock is considered affordable.[100] Through its zoning board of appeals, a municipality may authorize affordable housing by issuing a comprehensive permit that replaces all other local approvals.[101] Depending on the specific requirements of federal- or state-sponsored housing programs, at least 20 to 25% of the units in the project must be priced below market.[102] The local appeals board may deny the application outright or attach conditions before approving the comprehensive permit.[103] If those conditions render the project "uneconomic," or if the permit is simply denied, the developer may appeal to an administrative agency, the Housing Appeals Committee (HAC).[104]

HAC will reverse the local board of appeals and permit the project to go forward[105] unless the municipality demonstrates that the conditions it has imposed are consistent with local needs.[106] Basically, the local appeals board must first show that "valid health, safety, envi[*PG454]ronmental, design, open space or other local concern . . . supports such denial [or conditions], and then, that such concern outweighs the regional housing need."[107] Furthermore, if denial or conditional approval is based on a lack of municipal services or infrastructure, the local appeals board also must demonstrate that it would not be technically or financially feasible to provide them—with financial constraints relevant only "where there is evidence of unusual topographical, environmental, or other physical circumstances . . . ."[108]

This burden is difficult to meet, given the regulatory presumptions that HAC regulations impose: if a city or town does not satisfy one of four affordable housing thresholds—the primary one being that affordable housing units exceed more than 10% of the community's total housing stock[109]—there arises a rebuttable presumption that "substantial regional housing need . . . outweighs local concerns."[110] Unless the municipality meets one of the statutory minima and is, therefore, conclusively presumed to have satisfied the "local needs" test, it will most certainly either lose its appeal outright or be required to settle the matter on terms favorable to the developer.[111]

... surprisingly, the top priority of the Massachusetts affordable housing program is the development of low- and moderate-income housing, not environmental protection.[112] Nonetheless, the Comprehensive Permit Law embodies an awareness that legitimate environmental concerns must be taken into account.[113] Indeed, the power [*PG455]delegated to local appeals boards to issue a single municipal permit that overrides local zoning—and the power of disappointed

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developers to obtain one on appeal—has no impact on the enforcement of state or federal environmental laws and regulations. Even some decisions of local conservation commissions and boards of health are unaffected by 40B,[114] because the State has delegated to these bodies the authority to administer a "comprehensive state statutory or regulatory gram"[115]—such as the Wetlands Protection Act or septic system permitting under title 5 of the State Environmental de.[116]

Several elements of the Massachusetts affordable housing program should, at least in theory, deflect the perception that the Comprehensive Permit Law weakens environmental protection.[117] First, the 40B program includes incentives that encourage the development of affordable rental housing. A municipality may count all units—both market-rate and below-market—in calculating its 10% affordable housing threshold, an advantage generally not available if mixed-income housing is to be sold.[118] Because rental projects are more likely to achieve higher levels of density, they naturally fit better into a community's environmental goals. Second, as discussed below, the 40B process rewards planning.[119]

[*PG456] Third, although various thresholds—particularly the 10% affordability target—may be low,[120] once one of them has been met, communities have greater discretion in determining whether, and how, to pursue additional affordable development. Thus, despite the goal of the 40B program to enhance income diversity on a geographical basis,[121] it may not be the engine of unplanned rural development that some critics claim.[122]

Fourth, although a choice by city residents to relocate to affordable housing in the suburbs might contribute to sprawl,[123] virtually no data suggest that this has happened.[124] Moreover, as a general proposition, the Comprehensive Permit Law appears to function more successfully in urban environments.[125] Of the thirty-two municipalities [*PG457]over the threshold by year 2003, nineteen were cities or older industrial centers such as Boston, Worcester, Lowell, and Holyoke.[126]

Finally, the Massachusetts affordable housing program, unlike those in New Jersey and Oregon, requires that the projects receive some type of subsidy.[127] Environmental impacts will vary depending on the structure of the subsidy program.

lication of the affordable housing mandate on a town-by-town basis, in combination with a trend towards intra-proj cross-subsidization,[128] has made 40B appear to be more threatening to the environment than its authors may have intended. At the moment, much 40B development consists of non-rental units in the form of detached dwellings.[129] This promotes sprawl.

Specifically, for the past decade, the subsidy program of choice has been the Department of Housing and Community Development's (Department) Local Initiative Program (LIP), which requires local participation and approval.[130] At first blush, it would seem that the impacts of LIP housing would be relatively modest. A LIP project must be approved by the local executive, and up to 70% of its units may be reserved for those with local ties. In addition, the projects tend to be small, usually no more than twenty-five units, and often no more than eight.[131] But that is not precisely so.

LIP projects satisfy the public support requirement by accepting technical assistance from the Department. In the absence of a monetary subsidy, builders compensate in two ways for the lower profit or loss they must take on the affordable units. First, they stick to moderate-income housing; then they ensure that 75% of the units are offered at market rate.[132] These dual imperatives pull them in one di[*PG458]rection, toward single-family housing. In fact, some 90% of all LIP projects consist of single-family homes. The affordable component has been reserved for middle-income owners, with priority often accorded to those with local ties or the elderly.[133]

A growing number of 40B units in the past few years have qualified under a non-governmental program, the New England Fund (NEF).[134] Operated by the Federal Home Loan Bank of Boston, the NEF provides affordable housing loans through member banks. In the past, many local lenders have supported sprawl-inducing "greenfield" projects. But as a result of HAC's recent round of regulatory amendments, the Department may designate a public or quasi-public entity to issue site ovals for NEF housing, and later monitor compliance with the Comprehensive Permit Law.[135] Thus the State is empowered to adopt review criteria to examine whether these projects induce sprawl or otherwise harm the environment.[136]

[*PG459] Less direct influences on developers also play a role. Though data are lacking, it is predictable that a builder will

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prefer to seek a comprehensive permit for a site that is not otherwise desirable or developable. Such a site is likely to offer three advantages: (1) low development costs; (2) relatively few potentially objecting neighbors; and (3) the opportunity to bypass local regulatory constraints, such as zoning restrictions or subdivision review by planning boards.[137] The first ...antage is likely to be more available in relatively undeveloped areas.[138] As for the second, nearby residents may cause ...itical problems and, if able to demonstrate special damages, may sue in superior court to challenge a comprehensive permit.[139] The third feature is relevant because it creates the circumstances under which the regulatory relief offered by 40B becomes a valuable commodity. Thus, the paradigmatic 40B parcel is more likely to be situated within reach of existing infrastructure, yet outside the ambit of sensitive areas regulated by state environmental laws—such as wetlands or rare species habitat.[140]

Together, these forces create a weak incentive, promoting dispersed development and its sprawl-related impacts. Furthermore, the Massachusetts affordable housing program does little to integrate the fundamental goals of the Comprehensive Permit Law with concern [*PG460]about the environmental impacts of sprawl.[141] The former approach looks at numbers; the latter at dynamic systems.

HAC has made an effort to fill this gap. Although characterized at times as distant and insensitive to local concerns,[142] the five-member HAC appears to strike a cautious balance between housing and the environment. It serves as a sort of truth squad to counteract the municipal predilection to determine that affordable housing must yield to the community's strongly held environmental values. The numbers alone underscore the inherent power of the Comprehensive Permit Law. As of 1999, developers had filed more than 300 appeals of local decisions, and one half had been formally adjudicated. Of these, HAC reversed ninety-four and upheld eighteen, a ratio of more than five-to-one.[143] Many decisions involved allegations by the local appeals board that the proposed development failed to meet local needs because of harm to the environment.

Nonetheless, a review of relevant decisions supports the view that HAC has taken to heart its obligation to balance housing and the environment in the course of evaluating the frequently-voiced concerns that a proposed 40B development will ...promise public health, consume valuable open space, and degrade natural surroundings.[144] Cases before HAC raise ...vironmental issues in several distinct, albeit overlapping, settings. The first involves allegations by the municipality that local policies establish a protective standard precluding the proposed affordable housing project. Sometimes it is based on general environmental concerns, rather than local regulation. HAC will accord such "standards" little weight.[145] It is interesting to note that no decisions so far appears to have presented a direct conflict between local environmental regulation and affordable housing.[146]

[*PG461] In the second setting, a developer demonstrates that a city or town seeks to apply local environmental standards more rigorously in the face of an affordable housing proposal.[147] HAC has made it clear that a city or town will not be heard to argue that, if approved, the 40B proposal will be the straw that breaks the environment's back, at least where the municipality has been more lax with other, market-rate projects.[148] As HAC wrote a decade ago, where "there is no clear-cut standard to be reviewed, . . . the Committee has often found as a factual matter that there is no significant danger to the public health or safety."[149]

A third setting involves a failure of proof. This is perhaps the most troubling because the ultimate judgment by the local agency (here, the appeals board) is not accorded the level of deference customary in many appellate forums. Rather, HAC reviews the evidence de novo,[150] with the municipality under a heavy burden to demonstrate the importance of its environmental concerns. In effect, HAC sits as a quasi-environmental regulator, but without the depth of expertise typically available to a larger agency.[151] When the developer's experts disagree with the local board, HAC may be called upon to resolve complex scientific questions.[152] Given that the municipality [*PG462]bears the burden of proof, HAC usually finds for the project proponent.[153]

...urth setting is directly related to sprawl: Does a municipality have the power to deny access to local infrastructure like ...r and sewer service, or to require that the developer pay for the marginal increase in load on the existing system? HAC decided recently that the local board may require a 40B developer to mitigate "specific" problems created by the new development itself.[154] But it did not explain in detail how to differentiate the specific from the general, except to suggest that mitigation measures must take place in the vicinity of the project itself.[155] It is difficult to assess what effect HAC's

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approach will have, particularly if local efforts to internalize marginal costs are not applied equally to all development.

Overall, HAC's decisions send a message that major environmental concerns will be reviewed with care only when they are ented with specificity. When a town asserted that its density restrictions were linked to environmental protection, H erved that "no meaningful analysis is possible at that level of generality."[156] When, in a rare opinion affirming the loca board's decision, HAC upheld the installment of septic systems—rather than a sewer tie-in—for a twelve-unit low-income housing project, it required that monitoring wells be installed and operated under the supervision of the town's planning board.[157]

In another recent case, a builder sought to construct a two-family house with one affordable unit on a vacant lot in a residential area near a town center, a project HAC described as "a textbook example of in-fill housing."[158] HAC noted that the recycling of existing lots [*PG463]"typically raises fewer environmental concerns than so-called 'greenfields' development," and represents "smart growth" winning out over "urban sprawl."[159] Finally, in late 2002, HAC again tackled the problem of sprawl, requiring that a permit be issued for a ten-story apartment building with 183 units of mixed-income rental housing to be located near a large suburban mall, other shopping areas, transit nodes, a state park, and a rail trail.

Recently, HAC set forth its clearest statement to date of what might be called the principle of planning priority—the idea that in appropriate cases a local board's denial of a permit will be upheld if the project is inconsistent with a municipal plan, provided the plan is bona fide and sufficiently inclusive.[160] For example, by a three-to-two vote, in *Stuborn Limited Partnership v. Barnstable Board of Appeals*, HAC upheld the denial of a comprehensive permit for a thirty-two-unit retirement condominium located on the town harbor.[161]

HAC has articulated a two-part test to evaluate comprehensive plans. The first part focuses on whether the plan is legitimate and viable, promotes affordable housing, and has been implemented in the project's proposed location. The second part of the test is to determine how much weight to give the plan in light of the results of the first part, as well as the extent to which "the provisions of the plan are unnecessarily restrictive as applied specifically to the proposed ect."[162]

In *Stuborn*, HAC found that the Town of Barnstable had indeed developed strategies to stimulate affordable housing, including new multifamily housing districts, construction incentives, and detailed municipal plans that focused on housing.[163] In addition, the comprehensive plan had been implemented in the section of town where the [*PG464] affordable housing project would be built, and without exception, this area had been zoned for marine business use.[164]

In reaching its conclusion, HAC rejected the developer's argument that "housing would be friendlier to the environment than the marine use proposed by the [local appeals] Board."[165] While noting that any project could have an impact on the environment, HAC treated marine-related development as almost a rarity of nature: "Harbors are distinct, limited resources, and the interest in preserving them is even stronger than many of the more general planning interests articulated in local comprehensive plans."[166]

Although the *Stuborn* ruling does not answer every question,[167] it signals that municipalities willing to envision a future that includes affordable housing will find ways to achieve their overall land use goals, provided this is accomplished through a comprehensive planning process that is concrete and enforceable. This is the sort of planning regime that is likely to mitigate sprawl.[168]

### B. *New Jersey's Regional Fair Share: A Constitutional Directive*

Unlike the Comprehensive Permit Law, which has been copied by several other jurisdictions,[169] the evolution of New Jersey's approach to affordable housing is *sui generis*.[170] A reformist New Jersey [*PG465]Supreme Court announced a new rine founded on the state constitution that became the first step in the articulation of more detailed requirements for creating statewide low- and moderate-income housing opportunities.[171] Both the case that announced first principles, a the subsequent one that sharpened them into a powerful program, involved the then-small township of Mount Laurel,[172] located about ten miles east of Camden, in southern New Jersey.[173] A third decision often regarded as the final step in the judicial development of the State's affordable housing policy found that the legislative response to the first two rulings—to

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establish an administrative process to implement the policy—did not violate New Jersey's nascent constitutional right to affordable housing.[174] The history and political and social drama of what is widely known as the *Mount Laurel* doctrine have been recounted in extensive and illuminating detail elsewhere.[175]

... some ways, the *Mount Laurel* doctrine, as modified by the New Jersey Fair Housing Act of 1985,[176] is not unlike the Massachusetts Comprehensive Permit Law. Both programs give builders preference in siting affordable units until a municipality has met certain housing targets. Both are overseen by small administrative agencies.[177] And [*PG466]both incorporate environmental protection into their decision-making processes.

In New Jersey, the most densely populated state in the nation,[178] the potential environmental impacts of affordable housing were recognized in *Southern Burlington County NAACP v. Mount Laurel* (*Mount Laurel I*), more than a quarter century ago. In that case, Justice Frederick Hall announced that the New Jersey Constitution required every developing municipality in the state to meet its fair share of the region's affordable housing needs.[179] *Mount Laurel I* left many matters unresolved, such as the nature of the fair-share obligation and the manner in which its fulfillment would be policed. The court's treatment of environmental preservation was similarly vague: "This is not to say that land use regulations should not take due account of ecological or environmental factors or problems. Quite the contrary. Their importance . . . should always be considered."[180]

Eight years later, in *Southern Burlington County NAACP v. Mount Laurel* (*Mount Laurel II*), the New Jersey Supreme Court held that each municipality in a "growth area" must remove obstacles to affordable housing and take affirmative remedial steps to attract it—requiring, if necessary, developer incentives and housing set-asides.[181] Perhaps most importantly, the justices announced the so-called "builder's remedy." This permitted a disappointed developer to sue a municipality that had not provided its "fair share" of affordable housing. The [*PG467]trial court could then waive that community's zoning regulations to allow construction of higher-density housing, provided that at least 20% of the units satisfied low- and moderate-income guidelines.[182]

The *Mount Laurel II* court, expressing its optimism that "meeting housing needs is not necessarily incompatible with protecting the environment,"[183] attempted to strike a balance between "everyone's right" to green trees and flowers, and a constitutionally grounded opportunity to secure affordable housing all across the Garden State.[184] Throughout its more than 110 pages, Chief Justice Wilentz's opinion offered frequent reassurances that municipalities' newly-quantified obligation "to provide a realistic opportunity [to satisfy] a fair share of the region's present and prospective low and moderate income housing need"[185] did not extend to settings in which growth should be discouraged, such as open spaces, conservation land, prime farmland, and "environmentally sensitive areas."[186]

The court made several improvements upon *Mount Laurel I.* It transferred implementation to three handpicked trial judges[187] with orders to award a builder's remedy, a type of one-stop development approval, to qualifying affordable housing projects.[188] It broadened the housing obligation to include communities not in the process of development.[189] Further, it articulated centralized planning guidelines to help the trial courts and municipalities strike a balance between environmental protection and affordable housing.[190]

Two years later, the state legislature approved the Fair Housing Act, which established the Council on Affordable Housing (COAH), an agency under the leadership of an eleven-member council appointed by the governor.[191] The New Jersey Supreme Court held shortly thereafter that this transfer of day-to-day implementation of [*PG468]the *Mount Laurel* doctrine from the judicial to the administrative branch did not violate the state constitution.[192] COAH continues to be guided by these constitutional principles, and the environmental guidelines articulated in *Mount Laurel I* and *II.* Questions remain, however, about how well those guidelines are working.

'Jersey's *Mount Laurel* doctrine and the Massachusetts 40B program differ in one key respect: the former is founded state constitutional principle, the latter is not. Otherwise, both derive much force from variations on a single theme, the builder's remedy. In Massachusetts, builders must be public entities, nonprofits, or limited dividend corporations; proposed projects must receive public assistance of some sort; and generally at least 25% of the units must be "affordable." Proponents may obtain a local permitting waiver until the municipality has met a specified affordability threshold, which is

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typically 10%.

Despite the "steel"[193] that, eight years later, Chief Justice Wilentz sought to inject into the more credulous *Mount Laurel I* decision, the New Jersey affordable housing doctrine remains amorphous, and its enforcement heavily depends on a builder's remedy that in many ways resembles Massachusetts's 40B permit override mechanism. There are significant differences, however, between New Jersey's builder's remedy and 40B. First, need in New Jersey is based on a complex calculation that varies from municipality to municipality. Second, COAH has developed a certification process, which, in theory, now shields communities from builder's lawsuits for ten years.[194] Third, the builder of a project in which, generally, at least 20% of the units will be offered at low- and moderate-income prices may sue a resistant municipality to override local permitting requirements. Finally, through the much criticized Regional Contribution Agreement (RCA), a community can discharge up to half of its *Mount Laurel* obligation by funding affordable housing elsewhere, usually in economically disadvantaged urban areas.[195]

From the standpoint of environmental protection, however, the key departure from Justice Hall's pathbreaking opinion was the *Mount [*PG469]Laurel II* court's linking of constitutionally-mandated housing opportunities to New Jersey's nascent statewide planning process. The State Development Guide Plan (SDGP)[196] was issued without fanfare after several years of drafts and public hearings. In 1980, the SDGP offered the court "a statewide blueprint for future development."[197] In *Mount Laurel* disputes, the SDGP would "ensure that the imposition of fair share obligations will coincide with the State's regional planning goals and objectives."[198]

The court spoke of the SDGP as though its authority was self-evident,[199] even though it contained no obvious enforcement mechanism and was drawn up by an obscure agency. Yet, the SDGP served as a useful foil.[200]

The SDGP classifies land by development priority. It identifies areas suited to rapid development, with others to be given lower priority or maintained as open space, conservation land, environmentally sensitive ecosystem or farm.[201] By connecting the newly announced statewide affordable housing obligation to what he expansively characterized as a comprehensive growth plan, Chief Justice Wilentz was able to discard the vague "developing community" limitation and extend the *Mount Laurel* doctrine statewide, while avoiding the accusation that the court had set New Jersey's powerful development industry loose upon the countryside.

The *Mount Laurel II* court understood that, through the builder's remedy, it had created its own blueprint for market-driven housing reform.[202] Indeed, "it [would] be the unusual case that concludes the [*PG470]locus of the *Mount Laurel* obligation is different from that found in the SDGP."[203] The thumb has remained on housing's side of the scale.

Nonetheless, in practice, as in Massachusetts, lower courts could refuse to grant a builder's remedy "only if the proposed development . . . is contrary to sound planning principles, or represents a *substantial* environmental hazard."[204] Did this mean that more substantial proof of environmental risk would be required unless the municipality engaged in a formal planning process? Maybe. Muddying the waters further, the justices stated:

> [A] builder's remedy should be granted unless the municipality establishes that because of environmental or other substantial planning concerns, the plaintiff's proposed project is clearly contrary to sound land use planning. We emphasize that the builder's remedy should not be denied solely because the municipality prefers some other location for lower income housing, even if it is in fact a better site.[205]

Lower courts have come up with slightly different formulations of this directive.[206] The current view parallels that of Massachusetts: the municipality bears the burden of proving that a "site is environmentally constrained" or that the project represents "bad planning."[207]

Though statewide planning and housing policies in New Jersey were thus formally merged, did the participants in these two processes know that a union had taken place? This much is certain: statewide planning became more rigorous after *Mount Laurel II*.[208] In 1986, for [*PG471]example, the governor signed the State's planning act into law.[209] Nonetheless, planning efforts have not been rigorous enough to avoid the environmental impacts of the *Mount Laurel* doctrine reliably.

At present, the successor to the SDGP, the New Jersey State Development and Redevelopment Plan (SDRP), remains an advisory document. The State Planning Commission does not have the authority to enforce it.[210] A few courts have begun to apply some of the SDRP's provisions, however, and at least one agency has incorporated the SDRP's goals directly into regulations.[211] Ironically, that agency is COAH.[212] As a condition of certifying that a municipality is providing its fair share of *Mount Laurel* units—a designation that provides significant protection from builders' lawsuits for ten years[213]—COAH requires that the city or town demonstrate that it has met SDRP guidelines.[214] Specifically, it must show that its low- and moderate-income housing has been directed towards the appropriate planning areas, and generally steered away from those designated as rural or environmentally sensitive.[215]

COAH regulations require that municipalities exclude environmentally sensitive areas from their inventory of land potentially suitable for affordable housing.[216] This exclusion encompasses specific areas along the coast and in the Meadowlands, as well as much of the Pinelands, a huge area in southeastern New Jersey.[217] In addition, communities *may* exclude flood hazard areas, slopes, and inland wetlands.

[*PG472] Yet, COAH's authority is not great. Most of it is exercised in the certification of local affordable housing plans.[218] Like many agencies, COAH wields significant discretion in determining which provisions—so-called "housing elements"—are acceptable.[219]

Does this result in a sufficient level of environmental protection? COAH has been criticized for approving local plans that promote sprawl.[220] Moreover, only 265 of the state's 566 cities and towns have petitioned for certification.[221] COAH has awarded final approval to 199 of them, which represents just over a third of all jurisdictions.[222] In addition, the agency convinced SRDP[223] to allow affordable housing in agricultural and environmentally sensitive areas "when properly safeguarded."[224]

Apart from the possibility that those safeguards will prove inadequate, a systemic problem has arisen. First, much of the area not set aside as rural or environmentally sensitive is located in already-developed cities and older suburbs.[225] A significant percentage of this area may not be well suited to new development. Second, successive revisions of the state plan have led to the protection of an increasing [*PG473]inventory of agricultural and environmentally sensitive areas.[226] Finally, understanding of environmental risk has grown considerably since the first *Mount Laurel* suit was brought. The convergence of these forces is "potentially a time bomb,"[227] which could cause an explosion of poorly planned development in rural areas that now are valued as open space. Simply because COAH requires that greenfield development be clustered does not make it environmentally sound. Moreover, it does not greatly reduce the impact of one environmental risk that housing has the capacity to heighten: sprawl.[228]

Although some of the 301 municipalities that have not filed housing plans are weak candidates for certification, many are not. Those that have failed to file are targets for builder's remedy lawsuits. Thus, the power to harmonize housing and environmental goals remains in the hands of the courts.[229] The future of certification is difficult to predict, but the builder's remedy has been effective, albeit controversial,[230] in the past. Between 1983 and 1986, before COAH was established, more than 100 homebuilders brought lawsuits against approximately seventy municipalities.[231] In the past few years, dozens of additional lawsuits have been filed, and the recent record suggests that municipalities have lost most of them.[232]

Although many New Jersey cities and towns, under the pressure of the *Mount Laurel* doctrine, have rezoned to permit affordable housing, the builder's remedy appears to be driving the process. Moreover, [*PG474]most affordable housing units thereby created—whether a result of a successful builder's suit or a local housing plan (perhaps developed under threat of litigation)—include both market-rate and below-market units.[233] This approach raises environmental concerns.

The predominant development strategy—the builder's remedy—is closely associated with sprawl. It is a blunt instrument applied on a case-by-case basis, the antithesis of sound planning.[234] It favors the construction of freestanding housing over multi-al units, and much of the former is single-family.[235] For two general reasons, it is partial to large parcels. First, developers finance the low-cost units through cross-subsidies, and try to construct as many profitable units as possible. Second, development costs tend to be lower in less urbanized settings.[236] The result is additional pressure on COAH's less-than-completely successful effort to incorporate state planning policies into its affordable housing program. And, because

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the builder's remedy effectively sets 20% as the maximum[237] ratio of low-cost units to market-rate units,[238] the strategy of choice in New Jersey is one that calls for a great deal of market-rate housing to create one unit for its intended beneficiaries—whoever they may be.[239] Finally, the market itself may favor single-family units, and the *Mount Laurel* roach follows the market. A recent decision of the New Jersey Supreme Court confirmed that, in the face of such nand, an inclusionary housing plan may not satisfy a municipality's fair-share obligation if it provides too much multifamily housing and too little single-family housing.[240] This decision effectively permits one of the primary determinants of [*PG475]sprawl, a land-intensive lifestyle, to gain a stronger foothold in the affordable housing process.

In addition, the *Mount Laurel* fair-share obligation applies more or less equally to all cities and towns, and this favors more dispersed development than otherwise might be the case.[241] The *Mount Laurel I* court noted that "[f]requently it might be sounder to have more of such housing, like some specialized land uses, in one municipality in a region than in another, because of greater availability of suitable land, location of employment, accessibility of public transportation or some other significant reason."[242] But the idea of regional development "nodes" was rejected because, under New Jersey law, the municipalities in which these were sited would be required to bear the impact of likely decreases in the ratio of property tax revenue to the cost of providing local services.[243] New Jersey, like most states, requires that each city and town enforce zoning and levy property taxes individually.[244]

The environmental community is split over the effectiveness of the current approach.[245] One influential group recently proposed a system that engrafts an affordable housing requirement, as a fixed percentage of total development, on municipalities that are in a growth phase.[246] Proponents contend that this "growth share" strategy offers several advantages. It is fairer, more effectively protects the environment, permits stronger integration of regional planning and housing policies, will be easier to administer, and—importantly—will create more affordable housing.[247] The proposed system would site that housing in a manner that makes environmental sense, without bringing into play the equity issues raised by Regional Contribution Agreements.[248] But any move to embrace this, or any other approach, [*PG476]will have to come from the legislative branch of state government. Ever since it resoundingly endorsed delegation to COAH in 1986,[249] the New Jersey Supreme Court has done nothing to encourage the belief that it would revisit and adjust the ping principles it announced in *Mount Laurel I*, or to involve itself in matters of program design. In New Jersey, affordable housing doctrine teeters uncomfortably between a policy excursion and comprehensive planning.

C. *Oregon: Statewide Integrated Planning*

Oregon is different. It started planning years ago,[250] and at that time it focused on growth, not housing.[251] With only a few partial exceptions, nothing like the Oregon approach exists—or has ever existed—in the United States.[252] Planning, Oregon-style, is widely regarded to be the gold standard.[253] The key and often unstated question is whether the Oregon way is portable.

Since enactment of Senate Bill 100, sometimes referred to as the Oregon Land Use Planning Act of 1973 (Land Use Act),[254] Oregon has attempted to balance environmental and economic concerns within a unified system that carefully weighs regional political considerations. The Land Use Act set statewide planning requirements and established the institutional structure to carry them out.[255] First, the Land Use Act required that all cities and counties adopt new comprehensive land use plans consistent with statewide planning goals.[256] It also required those entities to promulgate regulations to implement [*PG477]the comprehensive plans, and to ensure that the new rules also were consistent with statewide goals.[257]

To implement this new program, the Land Use Act created a seven-member citizens body, the Land Conservation and Development Commission (LCDC), and established an agency, the Department of Land Conservation and Development (DLCD), to provide it with staff support.[258] The LCDC adopted fourteen—soon after increased to nineteen—statewide planning goals.[259] At least half of the goals directly address environmental and natural resource matters, and virtually all elated to environmental protection.[260]

The Land Use Act required each local and regional comprehensive land use plan to be submitted to the LCDC to ensure consistency with the statewide program.[261] The LCDC was empowered to order a municipality to bring its plan or regulations into compliance with state goals.[262] If a plan was not developed or was inconsistent with those goals, then

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consistency review for each of that jurisdiction's development decisions could be required on an individual basis—an extraordinarily time-consuming and expensive process.[263] Municipal and county plans have, by now, largely been submitted and approved,[264] so the LCDC enforces the statewide planning policies embodied in its goals by periodically ...iting all local plans and review[*PG478]ing proposed plan amendments.[265] With regard to the latter, it generally ...ercises its enforcement authority by taking an appeal to an administrative body, the Land Use Board of Appeals (LUBA),[266] and subsequently, to the state's intermediate appellate tribunal, the Oregon Court of Appeals.[267]

Planning Goal 14 requires that each of Oregon's cities protect development over a twenty-year period and establish urban growth boundaries designed to accommodate areas best suited for compact patterns of habitation.[268] Goal 10 requires municipalities to create housing plans that inventory buildable land within the urban growth boundary, project future needs, and plan for and zone enough land to meet those needs.[269] The housing plan must address a variety of housing types, and "encourage the availability of adequate numbers of needed housing units [including multifamily units and manufactured homes] at price ranges and rent levels which are commensurate with the financial capabilities of Oregon households."[270] When a plan is amended, its urban growth boundaries must encompass enough buildable land to meet the estimated need for all types of housing, including affordable housing,[271] for the twenty-year horizon.[272]

The LCDC and the Oregon Legislature have made it clear that they consider the Goal 10 program, as incorporated in Goal 14's mandate for urban growth boundaries,[273] to embody the essence of *Mount Laurel*.[274] Echoes of the New Jersey doctrine can be discerned [*PG479]in the statutory requirement that affordable housing proposals be reviewed only pursuant to "clear and objective approval standards," and in the requirement that the need for such housing be met within urban growth areas.[275] Evidence suggests that the combined application of these two goals has promoted higher-density residential development.[276] The result has been relatively inexpensive housing that counteracts the effects of sprawl.[277]

This last claim has been subject to controversy. Some have argued that strictly enforced urban growth boundaries merely r...se the price of housing and eliminate the added affordability that clustering can provide.[278] Recent data, however, cast ...bt on these assertions.[279] Moreover, these critics miss a larger point: in Oregon, concerns about housing costs have ...placed concerns about exclusionary zoning. Although this might appear to be simply a variation upon a theme, the Massachusetts and New Jersey experiences suggest that, if the local polity does not accept the premise that affordable housing is needed in a diverse range of communities, a long and expensive struggle will [*PG480]ensue merely to site a relatively small number of relatively non-controversial examples of it.[280]

Oregon has gone beyond Massachusetts and New Jersey. The State long ago decided it wants low- and moderate-income housing and that it should be sited in growth clusters. It is now merely working out the details—where affordable housing units should go, and who should live there. The details are important, but the steps taken already by Oregon have advanced the debate markedly.

From an environmental perspective, the contrast is even sharper. Oregon is one of the few states—perhaps the only one—that has implemented a broadly effective growth management and sprawl-control program.[281] True, the program is a point on a continuum,[282] and it certainly has its critics, but the Oregon approach offers three features that commend it. First, as noted, it contains a strong top-down element. Second, justification arises from concern about the environment and land use, not housing.[283] Finally, it is enforced directly by a specialized government agency.[284]

In contrast, Massachusetts and New Jersey focus on the legal (and moral) responsibility of each municipality for its portion of affordable housing, termed "fair share," "regional share," or "proportionate share." To succeed in these states, action must begin at the grassroots, though often it does not. The Massachusetts and New Jersey programs are sequestered in the local in another way: achievement of their policy objectives depends on the presence of builders seeking to pursue specific projects. Those projects are driven by short-term economics, not by environmental protection or thoughtful, long-term ...ning.

[*PG481] The Oregon way has other advantages, including the benefit of long-term planning.[285] Further, with only 241 major local political jurisdictions, it is considerably less Balkanized than its eastern counterparts.[286] Eighty percent of Oregon's population lives in the 100-mile long Willamette Valley,[287] and, thus, is highly concentrated.[288] Unlike New

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England and the Atlantic states, it has a weaker home rule tradition.[289] The Willamette Valley also is Oregon's premier agricultural region; thus, the community contains a relatively strong counterweight to development interests.[290]

haps the question should not be whether other states can emulate Oregon's model. Instead, it should be whether ements of the model can survive elsewhere, complementing existing structures. If so, what is the optimal organization... transplant?

## CONCLUSION

In pressing for an RCA provision in the New Jersey Fair Housing Act, then-Governor Thomas Kean said that his objective was to inspire communities to engage in planning.[291] Based on the experiences of Massachusetts and Oregon, the converse might have been the better strategy: planning, under the right circumstances, can establish an appropriate incentive to create affordable housing.

Despite their controversial histories, the Massachusetts and New Jersey programs have met at least some benchmarks of success. Each, [*PG482]for example, has produced approximately 20,000 units of affordable housing.[292] These numbers are small, but not insignificant. Whether the programs have come close to meeting other goals, however, is another matter, and the extent to which those goals justify the investment is an open question.[293]

From an environmental standpoint, the Massachusetts and New Jersey initiatives suffer from an obvious defect—they are not coordinated with other policy objectives. As a result, they tend to be shaped by existing patterns of sprawl.

This lack of coordination is reinforced by the structure of the two programs. Both are founded on the concept that each community is responsible for a "personal" share of a larger region's housing needs, which may play into much-criticized notions of home rule and local autonomy. Additionally, states that follow the Massachusetts or New Jersey approach may dvertently mischaracterize the nature of the racial and class discrimination that affordable housing programs are sumably designed to ameliorate.[294] Indeed, this personalistic approach has been received as an accusation and resis This can increase program costs unnecessarily.[295] In addition, where a town-by-town affordable housing obligation is the default position, its successful pursuit will tend to promote sprawl.[296] Yet, no obvious way exists to balance this environmental impact against potential equity considerations.

Both the Massachusetts and New Jersey approaches require municipalities to allow more development than they otherwise might allow on their own. Massachusetts sets a clear numerical threshold, whereas New Jersey has a more complex process that, nevertheless, arrives at a similar result.

Both states rely on market-based approaches, such as the zoning waiver or the builder's remedy, to provide a regulatory subsidy to developers. At a time of rapidly diminishing public housing funds, the [*PG483]builder's remedy cross-subsidizes affordable units through sale of market-rate units.

Economics and existing practices favor housing that promotes sprawl. First, the required percentage of low-cost units is small,[297] and builders have little, if any, incentive to offer more. Second, the cross-subsidy favors building more profitable single-family homes. Because some of the potential profits are lost on the affordable units, developers have an even stronger reason to build the most profitable housing possible. Third, these economic signals tend to promote construction in locations that, although not necessarily the most environmentally sensitive open spaces, are nonetheless unconnected to other development or to public transit. Developers will seek such areas because they accommodate the kinds of housing that the cross-subsidy promotes and because land and development costs are likely to be lower in these locations. Collectively, these factors translate into sprawl.[298]

ı states have established institutions that ostensibly examine the environmental impacts of affordable housing with great care. There is some evidence that this strategy is working, particularly in Massachusetts, but it is also clear that, in showdown between affordable housing and the environment, housing has the edge. Low-cost units will likely be approved unless local environmental rules,[299] specifically prohibit them. Although the Massachusetts Housing Appeals Committee has done a particularly noteworthy job of evaluating a wide spectrum of environmental risks, it simply does not have the

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mandate to ensure that this will continue. Even the laws themselves—Chapter 40B in Massachusetts and New Jersey's *Mount Laurel* regime—require that close cases be decided in housing's favor.

-gon offers an alternative. Affordable housing in sufficient quantity to meet local needs could arise from a system of -datory statewide planning. Whether effective statewide planning can arise from a localized housing mandate, however, remains to be seen.

Right now, both Massachusetts and New Jersey have weak statewide planning, and, with few exceptions, neither State performs any [*PG484]regional planning. This makes for a poor fit because affordable housing goals in both states are expressed on a regional basis. But there is reason for optimism. New Jersey, at least, does have a plan, and COAH is attempting to enforce it. While that effort has not been entirely successful, it does provide the structure and some authority for denying the builder's remedy at sites where development will promote sprawl. Massachusetts effectively does no statewide planning, but HAC has articulated incentives for localized planning on a case-by-case basis. Communities with plans that provide for affordable housing have the authority to deny a comprehensive permit where a builder has violated the objectives of the plan.[300]

Although the opportunity to implement centrally enforced planning around urban growth boundaries may never arise in the northeast,[301] other approaches are available, even in Massachusetts. First, significant improvement could be achieved if individual cities and towns would plan for affordable housing, along with more efficient growth patterns.[302] Second, a revivified local process could generate consensus planning principles, albeit few and basic, that recommend themselves for adoption at the regional or state level. Third, even a bottom-up effort might accumulate sufficient momentum to spark legislative action, provided the action is narrowly focused. One attractive target in Massachusetts is its generous doctrine of vested rights. Right now, open space advocates contend that builders can take advantage of existing sprawl-friendly zoning for extensive periods merely by making a cursory gesture of their intent to develop.[303] Finally, de[*PG485]spite shortcomings, it is not clear that the planning vacuum in Massachusetts effectively stymies local attempts to coordinate growth and integrate housing, economic, and environmental goals. Even imperfect efforts could channel existing animus more positive way.

In New Jersey, where planning is somewhat more advanced, it may be possible to broaden the mandate of the State Development and Redevelopment Plan, or at least to incorporate its principles into additional agency rules and judicial decisions.[304] Also, the state might take inspiration from Oregon and adopt the "growth share" approach, which would link housing policy and environmental protection together more tightly.[305]

These would be small steps, but they could build on what now exists, rather than allow Oregon's widely remarked perfection to become the enemy of good-faith improvements elsewhere. Finally, it is important to maintain perspective, because affordable units, when all is said and done, account for but a small percentage of all housing starts.[306] The main burden of sprawl just might be coming from other quarters.[307]

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# State of Housing in Los Angeles

## Community Briefing Sessions

# Los Angeles Households Today

Data Source: Census 2000, 1990

| | 2000 | 1990 |
|---|---|---|
| **Average Household Size**<br>*1,275,412 households and 3.7 million residents* | 2.83 persons<br>• Renter 2.73<br>• Owner 2.99 | 2.86 persons<br>• Renter 2.76<br>• Owner 2.87 |
| **Median Household Income**<br>*U.S. Median Household Income - $41,994* | $36,687 | $30,925 |
| **% of Households Earning Less than $50,000**<br>*Households earning less than $25,000 = 35.1%*<br>*Households earning $25,000 - $50,000 = 27.4%*<br>*Households earning greater than $50,000 = 37.5%*<br>*U.S. % of Households Earning Less than $50,000 - 58%* | 62.5% | 71% |
| **% of Renter Households that are Severely Cost Burdened** (paying more than 50% of household income to rent) | 22.6% | Unavailable |
| **% of Renter Households**<br>*U.S. % of Renter Households – 34%* | 61.4% | 60.6% |
| **% of Owner Households**<br>*U.S.% of Owner Households – 66%* | 38.6% | 39.4% |
| **Severely Overcrowded Households** (more than 1.51 persons per room)<br>U.S. Severely Overcrowded Households – 2.1% | 18.1% | 15.7% |
| **% of Households with Head of House Aged Between 25-34 Years** | 22.9% | 25% |

Housing Affordability:

- Average rent for two bedroom/two bathroom apartment: $1,652 (Source: RealFacts 2003Q2)
- Hourly wage required to pay average rent $32 - or $66,560/year (Source: Dataquick, 10/19/03, *LA Times*)
- Median priced home: $333,250 vs. U.S. median priced home $172,300 (Source: September 2003, California Association of Realtors)
- Hourly wage required to purchase median priced home: $31 - or $64,753/year (assumes 6% interest and 5% down on a 30-year loan)

## Why Care?

- In Los Angeles 25% of renter households are severely overcrowded (*more than 1.51 persons per room*), and 8% of owner households are severely overcrowded - versus 5.8% of U.S. renter households and 1.2% of U.S. owner households. Household overcrowding:
  - Stresses infrastructure
  - Affects living conditions
  - Affects community health
  - Creates unsafe living conditions, such as living in garages, attics, room conversions

- Nearly 2/3 of households earn <u>less</u> than the minimum income required to afford average apartment rent or median home price. Who earns less than $50,000 per year:
  - Fast Food Workers $14,800/year
  - Nurses Aides $18,800/year
  - Janitors $27,500/year (unionized)
  - Administrative Assistants $30,368/year
  - Grade School Teacher $40,100/year
  - Registered Nurse $47,700/year
  - Firefighter $45,800/year
  - Police Officer $49,400/year

- Severely cost burdened – 14% of LA households that pay more than half their household income, which allows for less money to be spent towards transportation, childcare, health care and other necessities.

- Household income has not increased at the same rate of rental and housing price increases

- City of renters – nearly 2/3 of households are renters
  - Renters do not receive tax benefits of home ownership
  - Home ownership stabilizes neighborhoods
  - Los Angeles is a city of renter - opposite of national renter average of 34%

- Los Angeles is not producing sufficient housing units to meet its need:
  - Housing Element estimates the City needs to build approximately 8,600 units per year to accommodate its housing needs.
  - Between 1999-2003 housing production has averaged 4,800/year – a shortage of 3,800 units per year. The good news is that the City expects to build 10,000 units in 2003.
  - Nearly half of the estimated housing need (4,047 units) is to be provided for low income residents – this means $31,600/year for a single resident and $45,100 for a family of four (HUD income limits for Low Income – Los Angeles/Long Beach PMSA, as of 02/20/03). Historically LAHD has invested in approximately 1,000 units of housing for working singles and families earning these salaries, and other private development adds to this as well. More work must be done.
  - Factors influencing housing development include availability and cost of land, construction costs, interest rates, unemployment/economic factors, neighborhood acceptance and City processes.
  - Up to 236,400 men, women and children are homeless in the course of a year and up to 84,000 people are homeless each night in Los Angeles County, according to a 1995 analysis conducted by Shelter Partnership, Inc. Approximately 46-40% of them are within the City of Los Angeles (Source: Institute for the Study of Homelessness and Poverty at the Weingart Center).

# What Has Los Angeles Done to Address the Housing Crisis

- Creation of Los Angeles Housing Department and Affordable Housing Commission in 1990.
- Regulatory/Zoning changes such as the Adaptive Reuse Ordinance and the Residential Accessory Services Zone.
- Rent Stabilization Ordinance (RSO) – citywide ordinance that protects tenants from excessive rent increases, while at the same time allowing landlords a reasonable return on their investments. RSO applies to all properties built prior to October 1978. Currently the City has 56,295 registered properties with approximately 555,000 units.
- Systematic Code Enforcement Program (SCEP) – citywide program created in 1997 that inspects all rental (except single family homes) property to ensure that State health and safety code requirements are met. To date the SCEP staff has inspected over 526,000 units and issued 1.3 million code violations (86% of all violations are resolved within 120 days).
- Home Ownership Opportunities through soft second program, home improvement loans to qualified families and elderly. LAHD has and continues to invest millions of dollars for home ownership and home improvement opportunities.
- Housing Opportunities for Persons with AIDS (HOPWA). LAHD administers the federally funded program that provides a full range of resources to those living with HIV/AIDS.
- $100 Million Affordable Housing Trust Fund – cooperative effort by Mayor, City Council, Staff and Advocates that created the largest municipal housing trust fund in the country. To date the trust fund has provided investment for the following:
    - Funding for development and preservation of hundreds of multifamily units
    - Emergency relocation services
    - Leveraging Trust Fund dollars with other sources for increased development
- Major Rehabilitation – collaborative effort in 2003 that provides RSO property owners with a reasonable rental increase in return for property improvements, without displacing elderly or long-term residents.

## Trends

- Increased funding to address citywide housing needs
- Leveraging funding to "stretch the dollars"
- More housing development along commercial corridors
- Adaptive Reuse Ordinance
- Neighborhood Involvement

# What More Can Los Angeles Do to Build More Housing

- Preserve Existing Affordable Housing – City of Los Angeles Affordable Housing Preservation Program (currently in development), continued support for funding of Section 8 rental assistance program and tenant protections.
  - Affordable Housing Database – LAHD maintains a database of affordable housing resources citywide, and plans to provide the detailed information on the web in early 2004. Additionally, LAHD is working with the community to collect information on accessibility to its affordable housing, which will also be provided on our website and to other stakeholders, including the Department of Disability and Living Independently in Los Angles (LILA).
- Develop housing along transportation corridors (smart growth principles), as called for in the City's General Plan Framework.
- Inclusionary Zoning Ordinance – Los Angeles is currently considering a policy that would require market rate housing developers to "include" a percentage of housing units affordable to working families. This practice would provide needed affordable housing units throughout Los Angeles, economically integrated housing communities and incentivize housing development. Such an ordinance could be crafted to suit the unique Los Angeles environment.
- Outreach and education for community stakeholders and developers
- Aggressively pursue Los Angeles' share of State and Federal funding for housing development, rehabilitation and preservation.
- Regulatory and Land Use Changes to facilitate housing development
- Housing Element – The Housing Element consists of an identification and analysis of existing and projected housing needs of all economic segments of the community. Current Housing Element is n effect from 1998-2005 and can be found at the Planning Department's website http://www.lacity.org/PLN/
- Bring LA Home – the Partnership to End Homelessness. Bring LA Home is a comprehensive and focused effort with the goal of ending homelessness by the year 2013 that was convened by more than 50 leaders of government, faith-based, social service, advocacy, entertainment, law enforcement, business organizations and people who have experienced homelessness.
- Incentivize Housing Development:
  - Provide funding to bridge affordability gap
  - Infill development
  - Mixed-use
  - Density
  - Expedite Processing

## What are your needs?

## Other Comments?

NHI Shelterforce Online

# January/February 1999: Sustainability Issue



**DEPARTMENTS**

NHI Shelterforce Online Issue #103, January/February 1999

# A Meeting of Movements

By Miriam Axel-Lute

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*In New York City the mayor tries to cast destruction of community gardens as a gain for housing advocates. Along the west coast, on-going battles pitch preservation of old-growth forests against retention of logging jobs. These struggles reflect an age-old assumption that open space preservation and affordable housing and job creation are mutually exclusive goals. Although many voices have spoken up over time to say it's a false choice, the perception still prevails. However, across the country some state-level coalitions of open space and affordable housing groups are not only refusing this divisive bait, but are actually linking issues into common platforms. They are changing not only the policy debate, but the way their members see themselves.*

To anyone concerned with both affordable housing and open space, the 12-year-old Vermont Housing and Conservation Trust Fund is seen as a model. Continuously funded and supported by Vermont legislatures and governors since its inception in 1987, this "dual goal" fund has made possible affordable housing for over 10,000 people and saved 165,000 acres of farms and valuable open space. A map showing towns in which the fund has financed projects is almost a solid swath of color. Mark Snelling, president of Shelburne Corporation, writes in the fund's 1997 annual report, "My sense is that the Housing and Conservation Trust Fund has made a dramatic difference. I think if people recall that feeling of loss that we shared in the late 80's there's no question that the situation is different now."

The need for the fund, and the coalition that made it happen, arose out of the 1980's real estate market in Vermont. Rapid growth was driving up the cost of housing; Section 8 owners were pre-paying mortgages and displacing low-income tenants with no warning; the same forces were pressuring farmers into selling land, gobbling up the farms and woods that to most Vermonters were the very essence of their state. Faced with a common enemy, and discovering a common interest in permanent solutions – permanent housing affordability and long-term land conservation – the state's land trusts, housers, historical preservation groups, and environmentalists joined efforts to form the Housing and Conservation Coalition (HCC). HCC hired an attorney, drafted language for a bill that would create a joint trust fund, and launched a successful lobbying effort to pass the bill.

But that's the thumbnail story, says Gus Seelig, current director of the Vermont Housing and Conservation Board (VHCB), the quasi-public corporation whose role it is to distribute the resources available from the trust fund. He says, "The realities that went into it took a lot of time and a lot of trust building." As James Libby Jr., a lawyer from Vermont Legal Aid who was present throughout the process wrote in an article for the February 1990 issue of *Clearinghouse Review*:

> During the first meeting two housing advocates joined a roomful of environmentalists, conservationists and rural planners who were on a 'first name' basis. At first, the housing advocates were fearful that affordable housing was being added because of its popular appeal and worried that conservationists, sometimes referred to as the 'green sneaker bunch' would not be able to understand or address poverty and homelessness. At the same time, the conservationists and farmers were afraid that the housing and low-income advocates would be too radical and too dogmatic to join the coalition.

These fears were slowly dispelled by the process of working together on a common goal, at least partially because their existence was not ignored.

Throughout HCC's work, balance has been paramount. The enabling statute for the fund stipulates "balance" in how the funds are spent, plus a requirement that VHCB justify itself if it spends more than 70 percent of the money on either housing or conservation in any given year. It never has. The composition of VHCB also addresses concerns of balance; two of four ex officio members must be heads of conservation groups, the other two must be heads of housing groups, and the five citizen members must include a low-income advocate and a farmer.

In fact, concerns of balance continue to be so strong that HCC, which still exists to see that the trust fund gets funded every year, has resisted any moves to go beyond that very limited function. "We often get asked to comment or take a stand on policies that come up in low-income or environmental areas, but we don't. That would risk divide and conquer," says Elizabeth Kulas of the Rutland County Community Land Trust, who has been active in the coalition since 1992 and served for three years as its co-chair. "The success we've had has been because we have stuck together even when people have tried to divide us. There are other coalitions [within each movement] that are better situated to take a stand on those things."

Their resolve has been impressive. Seelig describes how on a number of occasions state legislators have said things like: "Housing is not the issue of my party, but we'll give all the money to conservation" or "How can we possibly spend any money on

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conservation when people don't have housing?" But, even when millions of dollars have been offered to these causes separately, coalition members have have chosen the benefits of long-term cooperation over short-term gain, and stuck to the original design of letting the VHCB, not the legislature, divvy up the money. After all, working together got them this funding source to begin with. "Separate funds wouldn't fly," says Elizabeth Humstone, a former member of the VHCB and current director of Vermont Forum On Sprawl. "What allowed this fund to pass was one concerted effort." That unexpected cooperation is what got the attention, and eventually support, of then-State Senator Scudder Parker, says Humstone, who remembers him "saying something to the effect of 'I can't believe I'm seeing all of you sitting at this table together. This is really incredible.'"

**Taking a Unified Stand**

Unlike HCC's tight focus on a dual funding mechanism, one of the primary functions of New Jersey's Coalition for Affordable Housing and the Environment (CAHE) has been taking stands on certain public issues. But they too know the importance of being unified and the danger of divide and conquer. For example, over the past several years, a number of public officials turned to a superficial environmentalism to try to circumvent and undermine their town or district's requirements under New Jersey's fair-share affordable housing provision, known as "Mt. Laurel" after the court decision that established it [see *Shelterforce #93*]. These local officials and state legislators, mostly from rural areas, tried to blame affordable housing, rather than proliferating luxury housing and commercial strips, for the loss of New Jersey's remaining open space. But when New Jersey State Legislators began considering some bills in 1997 that would seriously weaken Mt. Laurel's fair housing measures, they found not only affordable housing advocates, but also environmentalists opposing them. "It definitely surprised some of the legislators," says Diane Sterner, director of the New Jersey Affordable Housing Network (AHN) and co-chair CAHE. The bills were defeated.

The unity opposing these bills wasn't serendipitous. It was one of the areas of common ground agreed upon by the fledgling CAHE. In the face of the attempts to pit them against each other, several housers and environmentalists in the state had figured there was strength in numbers and decided to pull together somehow. "It would be wrong to say there wasn't some mistrust between the two movements," says Paul Chrystie, the coalition's coordinator. "Not between the individual people, but the movements."

Therefore, the coalition has been deliberate and careful about trust building from the start. It began in Spring 1997 when members held a two-day retreat at which representatives from affordable housing advocacy groups, local CDCs, statewide environmental lobby groups, and local environmental groups aired previous

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baggage, respectfully discussed differences, and most of all explored common ground. "We discovered that we share a lot of the same goals," says Betsy Russell of Camden Lutheran Housing. One of the common themes that arose was how reinvesting in cities would help preserve open space, and how certain policies and practices were encouraging the opposite. Those participating in the retreat decided to create a formal coalition to explore ways of working together on the areas of agreement. And today, members of the coalition are quick to point out that what disagreements there are don't always split down a housing/environment fault line; often they arise from within one movement.

Current CAHE projects include defending the Mount Laurel doctrine, encouraging the State Planning Commission to pay attention to urban areas (and vice versa), advocating for property tax reform, and suggesting brownfields policy changes. As they suspected and hoped, there has been strength in numbers and unity. When a group called the New Jersey Coalition to Preserve Natural Resources was working to get a public question on open space preservation on the November 1998 ballot, CAHE held a press conference in support of the measure, pointing out its benefits for all locations, including the possibility of urban riverfront parks or tot lots. "Who knows for sure what part that played, but it showed the public and the legislature that this is not just for wealthy people out in the sticks who want to preserve the piece of space next to them," says Arnold Cohen of AHN. And while the coalition can't take credit for the measure passing, members can certainly take credit for the number of affordable housing groups who signed on in support of it. "That never would have happened without us," explains Chrystie, "because we were the meeting point."

That bridge building function has been one of the coalition's strong points, as the work of its State Plan committee shows. NJ's State Development and Redevelopment Plan designates growth centers, aims to control urban sprawl, and at least tries to take a comprehensive view of sustainable planning for the state. But once the plan was adopted in 1992, it fell off the radar of most CDCs and urban development folks in the state, and has been championed primarily by environmental groups. "There's a whole set of planning issues that we had not been following very closely," admits Sterner. "Affordable housing groups have their little geographic communities, and they generally work project by project."

But there was also good reason CDCs weren't enamored of the state planning process. They saw it as was weak on urban issues and not committed at all to involving them. So in February 1998 CAHE held a conference called "The State Plan: What's in it for Cities?" Attended by almost 175 people, the conference resulted in a series of recommendations for the State Planning Commission, including: fitting state agency expenditures to planning priorities, providing resources for urban areas to get involved in the planning process, and fostering regional and public/private partnerships, as well as specific recommendations on affordable housing, economic development, environment, and transportation. These recommendations were presented at the Planning Commission's April 22 meeting by co-chairs Diane Sterner and Sally Dudley. Their introductory letter says in no uncertain terms, "There is a real concern that the plan does not work, that its implementation lacks 'teeth,' and that to the extent that the plan works, it is solely a suburban exercise."

Despite these strong words, their presentation was enthusiastically received, and CAHE has continued working closely to build up the relationship between the planning commission and urban areas. It hasn't been an entirely smooth process. CAHE members often mention that not one of the first round of public meetings held in Spring 1998 as part of a rigorous process of state plan "cross-acceptance" was held in an urban area or accessible to public transportation. But once the coalition fired off a letter, which Chrystie describes as 'snippy,' the locations of the next round of cross-acceptance meetings included a few urban sites. "It's a small step," says Dudley, but she sees it as part of a definite trend.

## Smart Growth

In many other states, environmental groups and housers have recently found themselves together in a different kind of coalition. Part of a national Smart Growth Network, these coalitions organize specifically around combating urban sprawl. They encompass business, environmentalists, housers, civic groups, government, and more. Since Smart Growth assumes agreement on a shared goal from the outset, the relation between housing and environmental groups in these coalitions has been managed in a less deliberate manner than the processes the Vermont and New Jersey coalitions went through. However, Smart Growth groups have been able to be very proactive about pushing policy changes.

Grow Smart Rhode Island is one place where the balance seems to be working. When the state's largest environmental group, Save the Bay, teamed up with preservationists to hold a conference on Smart Growth, the need to broaden the coalition even further was clear. "It's very important to have housers in the Grow Smart coalition," says Curt Spalding, Save the Bay's director. "We need housing, and a place for business to do their thing. The question is how. If Smart Growth doesn't meet those needs, it's not going to be effective." He doesn't see Smart Growth, however, as a collaboration of two or more agendas looking for common ground. "It has its own agenda," he says firmly.

And that agenda is working across the country to link practitioners in specific fields into a larger picture. Brenda Clement, director of Housing Network, Rhode Island's state association of CDCs, says she got involved in Grow Smart because as CDCs have "evolved and matured, we've realized that housing isn't enough. You have to look at transportation, jobs, the environment" Although Grow Smart's work so far may not have included much emphasis on specifically building bridges or balancing the two movements, it has provided a space to sit down and discuss the issues and intersections, a theme echoed by all participants. "It's going to be more and more important to be talking," says Clement.

The necessary talking isn't automatically happening in all Smart Growth endeavors, however. Take for example, Maryland, a state in the vanguard of Smart Growth, but without a formal working relationship between the state's CDCs and environmental groups. In Spring 1997 Maryland actually passed Smart Growth regulations that eliminated state subsidies to development outside cities and other county-designated growth centers. But the laws, meant to stop sprawl by eliminating subsidies for infrastructure, also have the effect of limiting the locations of affordable housing, thereby preserving suburbs for the rich, says Becky Sherblom of Maryland Center for Community Development. Agreeing in principle with Smart Growth, but worried about reconcentration of poverty, Sherblom tried to raise the issue of affordable housing's treatment under the regulations during the campaign to pass Smart Growth. The result? "We got a lot of abuse from the environmental groups," she says. "They thought that any questioning of Smart Growth was 'pro-sprawl.' We were rebuffed; slapped in the face."

It's a sticky issue, one of the many that those working at the intersection of these two movements deal with every day. Spalding uses it to reiterate the importance of having everyone at the table. "Everyone charges that Smart Growth is about protecting the wealthy and putting walls around communities," he says. "You need to make sure the approach is sensitive to housing, and to communities that need some development." On the other hand, he doesn't agree that affordable housing should be exempt from Smart Growth regulations. "We still don't want to pop affordable housing into to farm fields with no services accessible to them," he says. "If that's the agenda, I believe it's misdirected. Those with the wealth have always been able to build their country estates. But the other 95 percent of us have had to live near urban centers to be near the services. We need to understand that we can live in density and have healthy communities."

Nonetheless, the dangers are also clear as Sherblom recounts the suburban Maryland county council member who responded to a presentation on Smart Growth by saying "You mean if we just don't designate a growth area you can't build low-income housing here? Great!" "I thought 'Oh my God,'" Sherblom recalls. "We've sanctioned NIMBYism with Smart Growth."

**Building Trust**

These kinds of questions lie below the surface everywhere, but the coalitions in existence are betting that their formal working relationship, their cooperation where they have common ground, and their process of learning about each other will help diffuse the differences in the long run, or at least make them less acrimonious.

"People really do believe that we can disagree on some things and still work together, and then maybe we can come closer on the things we disagree on," says Sterner. She admits that in New Jersey, CAHE started from an easier point than groups in Maryland, since in New Jersey both sides were "equally frustrated with the way things were going. And we had a state plan and the fair housing acts in place." But it was also a very deliberate process that made the coalition work, beginning with the retreat, professional facilitation of the first several meetings, and consensus on a platform up front. Sally Dudley, coalition co-chair, and director of the Association of NJ Environmental Commissions (ANJEC), prefers this to other coalitions where "there hasn't been a formal agreement on goals until you're well into what you're doing. That gets messy."

One of the most essential things keeping the trust alive all along has been the membership setting the agenda. "If you had somebody come in," says Chrystie, "from one of the member groups or the outside, and say, 'these are what we should be focusing on' that would be a danger." Sterner agrees. She recommends that the first thing any similar coalition should do is establish a clear process for raising issues, making decisions, and taking stands. "We had a few flare ups early on because there were a few times when the steering committee thought it had the authority to act upon something that hadn't been worked through the full group. You have to make sure you don't lose your membership by getting out ahead of them," she says. "There's nothing to replace people being face to face in a deliberate process to really hear what other people are saying," concludes Cohen.

The benefits of face-to-face interaction have gone beyond specific policy and funding victories. The more intangible goals of learning and networking and exchanging perspectives have already begun to be a reality. In NJ, coalition members often contact each other for ideas before writing their own position papers. CDCs that manage property have learned about Integrated Pest Management from some of their environmental colleagues [see IPM resources below], and have thus been able to reduce the amount of toxic chemicals they use. The Affordable Housing Network did a workshop on infill housing for the Association of NJ Environmental Commissions. "Now [ANJEC] has learned that the whole idea of redirecting growth into the cities isn't quite that simple," says Cohen. In Vermont, just lobbying for the trust fund has really deepened the members' understanding of how the other groups work. After all "you have to know what you are talking about when you go into the legislature," says Kulas.

**Regionalism**

These coalitions have not only joined environmental and housing groups, but they have also brought together urban, suburban, and rural constituencies. "In NJ, not many other groups have been able to bridge that gap," says Chrystie. Regionalism wasn't CAHE's original goal, but in the process of making clear the relations between urban disinvestment and loss of open space, and of showing how certain policies hurt both environmental quality and the quality of life of low- and moderate-income people, suburban and urban groups have been talking to each other. They are beginning to see themselves as linked. (See Shelterforce #98) In fact, despite its name, some of the Coalition for Affordable Housing and the Environment's members talk about it as an urban/suburban coalition, never mentioning housing or environment as categories.

However, while a focus on fighting sprawl is a clear one with which to build regional cooperation, it may prove to be yet too narrow. Madeline Hoffman, director of Grassroots Environmental Organization, a member of CAHE, sees the emphasis on urban development vs. suburban open space as counterproductive. "It's easy to say 'they're bulldozing our farmland while we have abandoned sites in the city and that doesn't make sense,'" she says. "In the abstract there's a lot of agreement on that. But I remember saying initially that that made me very uncomfortable, because most of the undesirable development was going in the cities anyway. From an environmental justice point of view it's not a solution to build an incinerator in Newark just so we don't chop down a forest in a pristine suburban area. We need not to have incinerators." Hoffman points out that while the coalition managed to support the open space referendum, it failed to take a stand on another question on the ballot that amounted to a bailout of several incinerators.

Hoffman doesn't see these as fundamental flaws in the coalition. "I have a lot of faith that the people involved in this process can do this, and will do this. The fact that a coalition got together around this at all gives me hope," she says. But she wants the coalition to push itself to pay more attention to grassroots activists in both movements, ("have fewer meetings in Trenton," she suggests), and to remember that there are urban environmental groups that are working on questions such as toxics clean-up and environmental justice.

Despite the many challenges left ahead, these pioneering coalitions have brought affordable housing and environmental groups into dialogue. And in some cases, as Betsy Russell of

Camden Lutheran Housing says, not only are there more people on each side of the table, but "it's not even like opposite sides anymore." That's an impressive step for two movements that not long ago didn't have a meeting point at all. The assumption that affordable housing and jobs are incompatible with environmental conservation may finally be on its way out. Now we can get to work.



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**Contacts:**

- NJ Coalition for Affordable Housing and the Environment; Paul Chrystie, coordinator;
- PO Box 22194, Trenton, NJ 08607, 215-563-1927
- Vermont Housing and Conservation Coalition; Conservation co-chair: Jim Shallow,
- Audobon Society; 802-434-3068;
- Housing co-chairs: Connie Snow, Brattleboro Area Community Land Trust; 802-254-4604; Meg Pond, Vermont Community Loan Fund; 802-223-1448
- Vermont Housing and Conservation Board, 149 State Street, Monpelier, VT 05602, 802-828-3250, fax 802-828-3203
- Grow Smart Rhode Island; Sheila Brush, coordinator; 300 Richmond St Suite 200, Providence, RI 02903, 401-273-5711, fax 401-751-1915
- Affordable Housing Network of New Jersey, One West State Street, PO Box 1746, Trenton, NJ 08607; 609-393-3752.

**Additional Resources:**

- Smart Growth Network, www.smartgrowth.org
- Coalition for a Livable Future; Jill Fuglister, coordinator; 534 SW 3rd Ave Ste 300, Portland, OR 97204, 503-294-2889

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**IPM**

Integrated Pest Management is an approach to pest control that minimizes unnecessary pesticide use by using all available methods. This includes prevention, careful observation, bio-active or less toxic remedies, knowledge of pest life cycles, and appropriate timing of pesticide applications. It is used in agriculture, landscaping, schools, homes, and industrial settings. For more information:

- National Science Foundation's Virtual Center for Integrated Pest Management, The National Science Foundation, 4201 Wilson Boulevard, Arlington, Virginia 22230, 703-306-1234; http://cipm.ncsu.edu/index.html
- New York State Integrated Pest Management; Cornell University, New York; www.nysipm.cornell.edu
- IPM Practitioners Association, PO Box 10313, Eugene, OR 97440; 541-343-6969, www.efn.org/~ipmpa

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NHI Shelterforce Online Issue #103, January/February 1999

# Building Green

## Innovative builders work to change low-cost green housing from an oxymoron to an achievable goal.

**By Michelle Dean**

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One of the earliest experiments in ecologically aware affordable housing took place in Roosevelt, New Jersey, a WPA-era suburb, in the late 70s to early 80s. Architects of Roosevelt Senior Citizens' Housing, a HUD-assisted project and 1985 National Honor Award winner, set out to incorporate energy-efficiency within traditional designs. "Chimneys" housed rotary ventilators and south-facing windows captured the sun's energy for heating. Energy-efficient water heater designs and recycled materials were used for insulation. Site-planning insured optimum heating/cooling properties of location and natural landscape elements. Shading screens and solarium controls moderated energy flow within individual units. While Roosevelt, a low-scale and low-density project, was praised as "sensitive, innovative and imaginative," most tenants did not regularly operate the various energy saving devices, and so energy savings dependent on user-interaction suffered. The Roosevelt project demonstrated that to be most effective, conservation devices must be user-friendly, and preferably integral to the design and operation of the unit.

Low-cost green housing has long been an oxymoron that affordable builders have struggled to change. Until recently, ecologically-oriented construction has mostly been limited to high-cost developments and individual construction geared to people with deep pockets to fund superior technology and avant-garde solutions to environmental problems. To date, the most dedicated environmentalists build the most effective green housing, and commit time and effort to maintenance. Green building may require more up-front cost to attain long-term sustainability goals, and as such it often does not address low-income housing needs. Further, there are few concrete examples with which to develop overall strategies of production.

But exceptions do exist. A number of eco-conscious builders and organizations are tackling these problems with strategies designed to minimize energy and materials consumption and maximize efficiency and conservation. Building Innovation for Homeownership, a publication by HUD's Partnership for Advancing Technology in Housing and the Building Innovation for Homeownership program, profiles 63 award-winning low-cost housing developments that include innovations such as modular construction, energy-efficient design, structural insulated panels (SIPs), innovative site design and development, steel framing, panelized construction, masonry construction, "green" design, and HUD-code manufactured housing. Many of these strategies produce more cost-effective housing with sustainable elements. For example, steel framing is economical, conserves trees, and is recyclable; modulars can be sensitively designed and customized to take advantage of siting for energy and land conservation while being especially airtight and efficient. Good site management reduces waste, and factory construction enables cost-controlling measures for reinvestment in "green" materials. City Life, an infill development in Portland, Oregon, used structural insulated panel construction to achieve higher energy efficiency than a conventional stick-built house could. Unconventional, low-cost on-site materials like adobe, straw bales, and rammed earth have been used to eliminate transportation costs (no fuel), and provide excellent insulation. In some cases, salvage material was reused to build the lowest cost and arguably the greenest homes – epitomizing the green motto, "reduce, reuse, recycle."

On another front, the co-housing movement, a trend toward integrated village-like shared housing, has demonstrated that achieving high levels of sustainability is possible through dedicated community decision-making and planning. Some co-housers have accepted government funding that opens units within the development for lower-income households, but these are a rarity. A Cambridge, Massachusetts, 85-unit co-housing development includes two units purchased for low-income rental by the Cambridge Housing Authority. Going one step beyond conventional wisdom, the group is committed to a super-healthy indoor environment, the re-use of industrial sites for housing, solar energy, access to and use of public transportation, and diversity. Their energy costs are projected to be 60 percent less than the average. This complex is under study by Harvard University's School of Public Health and the U.S. Energy Department, asking, "what makes the most difference, the person or the house?"

**Energy Efficiency**

In some ways, the mainstream of ecological thinking has not changed much. Energy efficiency is the number one route to conservation and green ends. Energy efficiency has become the mantra on all levels of the building industry and has been embraced by government and private enterprise as a means to affect the costs of running a household, making housing more affordable.

The Energy Efficient Mortgage (EEM) is a federally-recognized program that finances energy saving improvements as part of the initial mortgage or in stretching the debt-to-income qualifying ratio on loans. Lowered monthly energy cost savings can be applied toward a larger loan repayment for more slender pocketbooks. The program is particularly effective in the resale market but can apply for new construction as well. A U.S. Department of Energy recommended Home Energy Rating (HERS) must be conducted to determine eligibility for an EEM at a cost of $100 – $300. Since mortgage interest is tax deductible, the cost of energy improvements is doubly cost-effective.

The State of New Jersey has just initiated a far-reaching, $5 million program called the Sustainable Development/Affordable Housing Pilot Program with the Department of Community Affairs (DCA) in collaboration with Public Service Electric and Gas (PSE&G) to promote this agenda. Other agencies involved are the New Jersey Housing and Mortgage Finance Agency, the New Jersey Department of Environmental Protection, the U.S. Environmental Protection Agency (EPA), the New Jersey Energy Office and the New Jersey Commerce and Economic Growth Commission. Sustainable development criteria include many aspects of building that incorporate principles of sound land use planning: minimize impact on the environment; conserve natural resources; encourage superior building design to enhance the health, safety, and well-being of residents; provide durable, low-cost, low-maintenance dwellings; and make optimum use of existing infrastructure. The pilot program is soliciting designs meeting these standards that, with the application of reasonable public subsidy, may be widely replicated by affordable housing developers. An integral component of the Pilot Program is the current PSE&G 5-Star program, based on the EPA's Energy Star Home program that provides financial incentives to builders whose construction incorporates energy-efficient features. The HERS rating method determines eligibility, which typically entails improved insulation and air sealing, better windows and mechanical systems, as well as efficient lighting, appliances, and ventilation improvements.

The long-term goals of the project are to transform the market by raising the standard of development to reflect these criteria. Creative approaches using proven techniques and market-ready technologies with potential for wide distribution are encouraged for both urban and suburban application. The concerted effort to produce a template and consensus of best available options and technology is a critical element defining the challenge to affordable builders: make it commonplace, universally accepted, globally available, and locally applicable so the technology becomes cheaper and easier to use. As the guesswork of a holistic approach lessens, options to increase efficiency will dominate the marketplace, driving costs down and quelling criticisms that sustainability is for an upscale market only.

These methods are now being used in a series of rehabs of 18 New York City-owned multi-family buildings by architect Chris Benedict and mechanical systems designer Henry Gifford. The Enterprise Foundation, the Joyce Mertz Gilmore Foundation, and the New York City Department of Housing Preservation and Development also participated in this project. Working closely together, the team of architect and mechanical engineer adopted a "Total Systems" approach to energy conservation. The building shells were dilapidated, century-old energy sinks. The $4.3 million budget for renovation included about 1 percent additional funds for energy-improvement: from features such as celluloseblown insulation (a 100 percent recycled paper product) to individual room thermostats and trickle ventilators to control temperature, energy use, and airflow into the airtight buildings. The improvements in some cases added to the initial cost but were projected to pay their cost within two years – a high-efficiency boiler/water heater, for example. As for the ventilation system, some costs were eliminated (ducting and chimney work) by careful planning and variances granted by the buildings commission, for work that was unnecessary for the "total system" to function. The architect even incorporated such healthy materials as exterior grade plywood indoors to control formaldehyde releases and hardwood flooring to eliminate chemical releases from carpets. The sophisticated "total systems" design and close collaboration between architect and engineer resulted in a comparable-cost rehab that enhances the occupants' homes while saving energy and insuring good health.

The materials and rationale are readily duplicable. Benedict explained in "Taking a Remodeling Beyond Skin Deep," an article by Jay Romano in Nov. 22, 1998, *The New York Times*, "As an architect my role changed from being just the artist to hands-on, really understanding everything that was happening in the building. And we're finding that by making energy efficiency our focus, we can't help but end up with healthier, more durable housing." Gifford elaborated, saying that architects are not noted for working closely with mechanical systems designers to improve the overall function and efficiency of their buildings – and are paid a percentage of costs, no matter what materials they employ. Collaborations like these will lead to more innovative and truly effective solutions to energy needs.

**What the Future Holds**

Many more such innovative solutions to complex issues of affordability and ecological sustainability are now available. In 1995, a group of architects, environmentalists, and builders met in Atlanta under the auspices of Habitat for Humanity, the Department of Energy, Global Green USA, and several private foundations to discuss the future of affordable sustainable housing. That June, Habitat established the Environmental Initiative Partnership, a resource library and outreach arm, to share information and promote creative problem-solving. A database of Construction and Environmental Resources documents the work of Habitat's affiliates in implementing its mission "to promote good stewardship of natural resources in the elimination of substandard housing and to raise awareness of the impact of human habitation on God's creation." As organizations like Habitat for Humanity make it an intrinsic part of their mission to incorporate ecologically sound materials and methodologies, a standardized template is being created to enable more builders to embrace green products. Habitat, the 19th largest builder of single-family homes in the U.S. in 1994, with 50,000 homes to its credit by 1996, is driving a movement towards responsible practices. Groups like Habitat and other nonprofits are challenging the for-profit housing industry to meet their standards. The equation of saving high-cost time while wasting low-cost materials is one many for-profit builders have employed to enhance their bottom line. While Habitat is able to circumvent the high costs of labor with a largely volunteer work force, even high-end builders have seen the economic benefits of fundamental changes like energy conservation enhancements.

Fewer than one percent of architects in the latest survey of the American Institute of Architects (500 of 58,000 members) listed affordable housing as a primary interest. It takes vision, innovation, and dedication to reconcile good environmental practices with cost-consciousness. Knitting person-centered and earth-conscious values together with affordability and universal access is not unattainable or frivolous. Low-cost housing developers are beginning to accept the creative challenge of finding sustainable solutions to good design, good health, and affordability.



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*Michelle Dean is a freelance writer living in the Northeast.*

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**Contacts:**

- Chris Benedict, registered architect: 212-353-2296
- Habitat for Humanity International, Construction and Environmental Resources, 912-924-6935; email: Const&Env@habitat.org
- Sustainable Development/Affordable Housing Pilot Program, New Jersey Dept. of Community Affairs, 609-633-6284.
- U. S. Environmental Protection Agency Energy-Star hotline, 888-STAR-YES for builders' information package and mortgage information; Energy-Star web page for approved materials,
- Green Village Co., 617-491-1888

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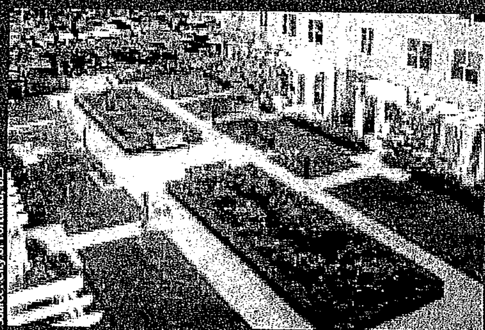
# What is Low Impact Development (LID)?

LID is an ecologically friendly approach to site development and storm water management that aims to mitigate development impacts to land, water, and air. The approach emphasizes the integration of site design and planning techniques that conserve natural systems and hydrologic functions on a site. The practice has been successfully integrated into many municipal development codes and storm water management ordinances throughout the United States. Specifically, LID aims to:

- Preserve Open Space and Minimize Land Disturbance;
- Protect Natural Systems and Processes (drainage ways, vegetation, soils, sensitive areas);
- Reexamine the Use and Sizing of Traditional Site Infrastructure (lots, streets, curbs, gutters, sidewalks) and Customize Site Design to Each Site;
- Incorporate Natural Site Elements (wetlands, stream corridors, mature forests) as Design Elements; and
- Decentralize and Micromanage Storm Water at its Source.



Source: City of Portland, BES

**Courtyard with Bioretention Areas**

Buckman Heights Community
Portland, OR

Cover Photo: R. Arendt

# Questions and Answers

Information on the most frequently asked low impact development questions.

Public Safety

Q: I am aware that in some instances, LID advocates the reduction of street widths and the reduced use of sidewalks to decrease impervious surfaces. Isn't this a threat to public safety?

A: No. Studies have shown that reduced street widths still provide all the functions of access, parking, and circulation for residents and emergency vehicles alike. Depending on density, minimizing the use of sidewalks may help to reduce development costs, increase housing affordability, and reduce impervious surfaces.

Q: Don't LID storm water management practices increase the likelihood of flooding?

A: No. LID designs provide adequate conveyance of storm water by using designs that maintain predevelopment volumes and rates of runoff. Since bioretention areas are designed to completely drain within a specified period of time, they do not provide breeding grounds for mosquitos. Overflow controls within bioretention areas control the risk of flooding.

Public Perception

Q: Aren't homeowners concerned about maintaining storm water controls on their properties?

A: Environmental stewardship is everyone's responsibility. Most homeowners view these systems as additional landscaping and once they are aware of the benefits that these systems provide to local hydrology, few remain opposed.

Maintenance

Q: LID practices sound great, but who maintains all of the open space and various storm water controls?

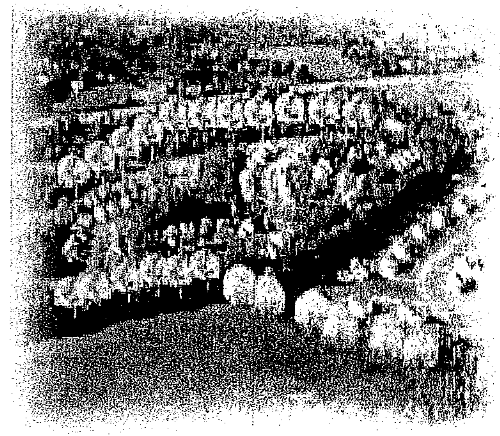
A: Communities designed using LID practices often rely on a combination of homeowner stewardship and maintenance agreements. When designed correctly, most homeowners perceive these systems as value-added builder amenities and actively provide for their maintenance.

# For More Information

- Low Impact Development Center
  http://www.lowimpactdevelopment.org
- Prince George's County, Maryland
  http://www.goprincegeorgescounty.com
- NAHB Research Center Toolbase Services
  http://www.toolbase.org
- U.S. EPA
  http://www.epa.gov/owow/nps/urban.html

NAHB Research Center

*Assumes paving costs of $15/sq. yd. ... d on recycled paper with soy ink



# Municipal Guide to Low Impact Development

Would you be interested in saving upwards of $70,000* per mile in street infrastructure costs by eliminating one lane of on-street parking on residential streets?

Did you know that communities designed to maximize open space and preserve mature vegetation are highly marketable and command higher lot prices?

Are you aware that most homeowners perceive Low Impact Development practices, such as bioretention, as favorable since such practices are viewed as additional builder landscaping?

Did you know that by reducing impervious surfaces, disconnecting runoff pathways, and using on-site infiltration techniques, you can reduce or eliminate the need for costly storm water ponds?

A005371

Source: Low Impact Development Center

Grassed Swale and Narrow Street
Montgomery County, MD

Source: Applied Ecological Services, Inc.

Bioretention with Native Vegetation
Prairie Crossing
Grayslake, IL

# LID Benefits

In addition to the practice just making good sense, low impact development techniques can offer many benefits to a variety of stakeholders.

Municipalities

- Protect regional flora and fauna
- Balance growth needs with environmental protection
- Reduce municipal infrastructure and utility maintenance costs (streets, curbs, gutters, sidewalks, storm sewer)
- Increase collaborative public/private partnerships

Developers

- Reduce land clearing and grading costs
- Potentially reduce infrastructure costs (streets, curbs, gutters, sidewalks)
- Reduce storm water management costs
- Potentially reduce impact fees and increases lot yields
- Increase lot and community marketability

Environment

- Preserve integrity of ecological and biological systems
- Protect site and regional water quality by reducing sediment, nutrient, and toxic loads to water bodies
- Reduce impacts to local terrestrial and aquatic plants and animals
- Preserve trees and natural vegetation

# Case Study

Somerset is an 80-acre development in Prince George's County, Maryland consisting of 199 homes on 10,000-square-foot lots. During its creation, the developer used LID practices to reduce the storm water management burden. By using LID, the developer:

- Eliminated the need for storm water ponds by using bioretention techniques saving approximately $300,000;
- Gained six additional lots and their associated revenues; and
- Reduced finished lot cost by approximately $4,000.

| Description | Conventional Design | Bioretention System |
|---|---|---|
| Engineering Redesign | 0 | $110,000 |
| Land Reclamation (6 lots x $40,000 Net) | 0 | <$240,000> |
| Total Costs | $2,457,843 | $1,541,461 |
| Total Costs (-Land Reclamation + Redesign Costs) | $2,457,843 | $1,671,461 |
| Total Cost Savings = $916,382 | | |
| Cost Savings Per Lot = $4,604 | | |

Source: D. Winogradoff

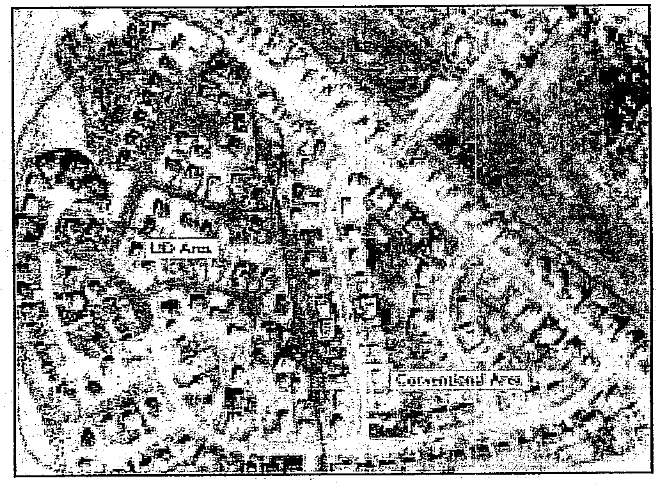
Cost Comparison: Conventional Design vs. Bioretention

Lot with Bioretention

Grassed Swale and Street without Curb and Gutter

Bioretention Area and Open Space

Photos: Low Impact Development Ce--




Aerial View of Somerset Development Site Plan, Prince George's County, MD

## Hydrologic Comparison between Conventional Storm Water Management and LID

Hydrologic alterations within the landscape occur whenever land is developed. Conventional development approaches to storm water management have used practices to quickly and efficiently convey water away from developed areas. Usually these practices are designed to control the peak runoff rate for predetermined storm events, usually the 2- and 10-year storms. While these systems have worked to some degree, they still have not accounted for the increased runoff rates and volumes from smaller, more frequent storms, nor have they addressed the larger watershed functions of storage, filtration, and infiltration.

In contrast, LID utilizes a system of source controls and small-scale, decentralized treatment practices to help maintain a hydrologically functional landscape. The conservation of open space, the reduction of impervious surfaces, and the use of small-scale storm water controls, such as bioretention, are just a few of the LID practices that can help maintain predevelopment hydrological conditions.

A005372

# What is Low Impact Development (LID)?

Ever wish you could simultaneously lower your site infrastructure costs, protect the environment, and increase your project's marketability? With LID techniques, you can. LID is an ecologically friendly approach to site development and storm water management that aims to mitigate development impacts to land, water, and air. The approach emphasizes the integration of site design and planning techniques that conserve the natural systems and hydrologic functions of a site.

Source: Prince George's County DER

Residential Lot with Bioretention

Somerset Development
Prince George's County, MD

## LID Benefits

In addition to the practice just making good sense, LID techniques can offer many benefits to a variety of stakeholders.

Developers
- Reduce land clearing and grading costs
- Potentially reduce infrastructure costs (streets, curbs, gutters, sidewalks)
- Reduce storm water management costs
- Potentially reduce impact fees and increase lot yield
- Increase lot and community marketability

Municipalities
- Protect regional flora and fauna
- Balance growth needs with environmental protection
- Reduces municipal infrastructure and utility maintenance costs (streets, curbs, gutters, sidewalks, storm sewer)
- Increase collaborative public/private partnerships

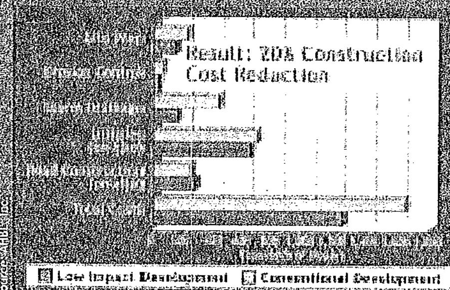
Environment
- Preserve integrity of ecological and biological systems
- Protect site and regional water quality by reducing sediment, nutrient, and toxic loads to water bodies
- Reduce impacts to local terrestrial and aquatic plants and animals
- Preserve trees and natural vegetation

Cover Ph[...]rendt

# Case Study

Kensington Estates is a conventional development on 24 acres consisting of 103 single family homes in Pierce County, WA. A study was conducted to redesign the site using a new state storm water model and to illustrate the full range of LID practices and technologies available to developers.

Overall, the redesigned LID site could have:
- Resulted in construction cost savings of over 20%;
- Preserved 62% of the site in open space;
- Maintained the project density of 103 lots;
- Reduced the size of storm pond structures and eliminated catchments and piped storm conveyances; and
- Achieved "zero" effective impervious surfaces.




Cost Comparison: LID vs. Conventional Development

Source: AHBL, Inc.

# For More Information

- Low Impact Development Center
  http://www.lowimpactdevelopment.org
- Prince George's County, Maryland
  http://www.goprincegeorgescounty.com
- NAHB Research Center Toolbase Services
  http://www.toolbase.org
- U.S. EPA
  http://www.epa.gov/owow/nps/urban.html

NAHB Research Center

*Assumes paving costs of $15/sq. yd.

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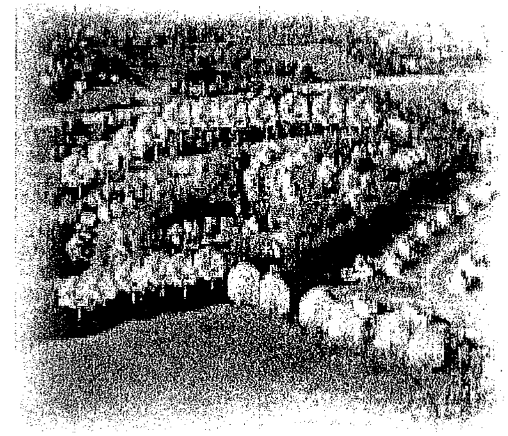


# Builder's Guide to Low Impact Development

Would you be interested in saving upwards of $70,000* per mile in street infrastructure costs by eliminating one lane of on-street parking on residential streets?

Did you know that communities designed to maximize open space and preserve mature vegetation are highly marketable and command higher lot prices?

Are you aware that most homeowners perceive Low Impact Development practices, such as bioretention, as favorable since such practices are viewed as additional builder landscaping?

Did you know that by reducing impervious surfaces, disconnecting runoff pathways, and using on-site infiltration techniques, you can reduce or eliminate the need for costly storm water ponds?

A005373

# LID Site Planning and Design Concepts

Successful LID projects simultaneously reduce land development and infrastructure costs while protecting a property's natural resources and functions. During the development process, the designer, developer, and reviewing agency should work together to identify solutions that integrate the following concepts:

- Preserve Open Space and Minimize Land Disturbance;
- Protect and Incorporate Natural Systems (wetlands, stream/wildlife corridors, mature forests) as Design Elements;
- Utilize Neo-Traditional Street and Lot Layouts and Designs; and
- Decentralize and Micromanage Storm Water at its Source Using LID Storm Water Management Practices.

## LID and Storm Water Management

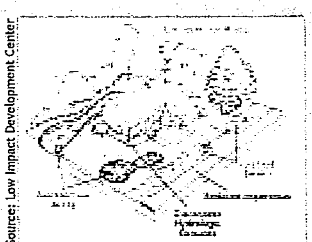
LID aims to mimic natural hydrology and processes by using small-scale, decentralized practices that infiltrate, evaporate, and transpire rainwater. Specifically, LID aims to:

- Minimize impervious surfaces;
- Disconnect hydrologic elements (roofs, downspouts, parking areas);
- Maintain/increase flow paths and times; and
- Utilize decentralized treatment practices.

Bioretention Areas
Storm water directed to these shallow topographic depressions in the landscape is filtered, stored, and infiltrated into the ground using specialized vegetation and engineered soils.

Grassed Swales
Water moving through these systems is slowed, filtered, and percolated into the ground. These systems can act as low cost alternatives to curbs, gutters, and pipes.

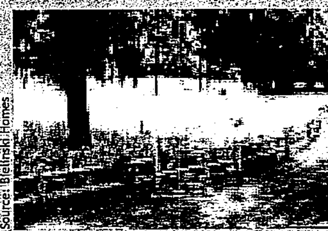
Source: Low Impact Development Center



LID Lot Level Source Controls

### Preserve Open Space and Minimize Land Disturbance

Source: Bielinski Homes



Community Open Space

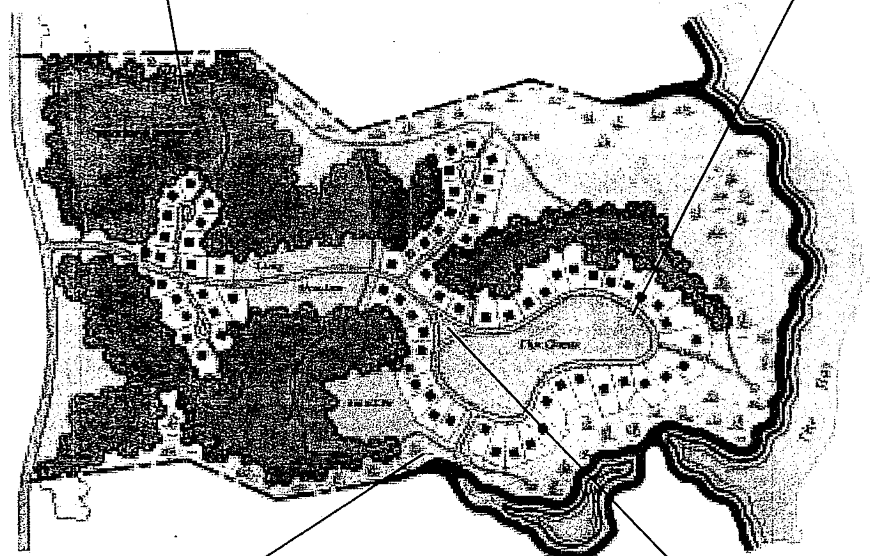
Bielinski Homes
Waukesha, WI

### Decentralize and Micromanage Storm Water at its Source using LID Storm Water Management Practices

Source: Low Impact Development Center

Grassed Swales

Somerset Development
Prince George's County, MD



From Conservation Design for Subdivisions: A Practical Guide to Creating Open Space Networks, by Randall G. Arendt. Copyright (©) 1996 by Island Press. Reprinted by permission of Island Press, Washington, D.C. and Covelo, CA.

### Protect and Incorporate Natural Systems as Design Elements

Source: Applied Ecological Services, Inc.

Wetland System

Prairie Crossing
Grayslake, IL

### Utilize Neo-Traditional Street and Lot Layouts and Designs

Source: DPZ & Co.

Bowman Park
Vermillion Community
Vermillion, NC

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Construction Waste Management
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NOTE: PDF documents require the free Adobe Reader.

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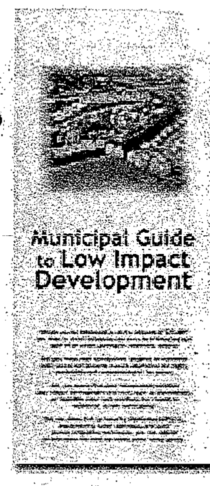
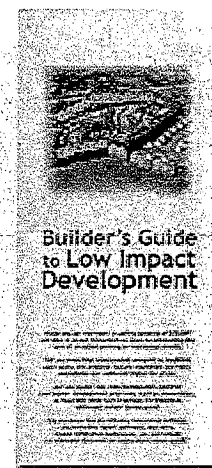
# Guides to Low Impact Development

Ever wish you could simultaneously lower your site infrastructure costs, protect the environment, and increase your project's marketability? Using Low Impact Development (LID) techniques you can. LID is an ecologically friendly approach to site development and storm water management that aims to mitigate development impacts to land, water, and air. The approach emphasizes the integration of site design and planning techniques that conserve natural systems and hydrologic functions on a site.




LID has a variety of benefits to Builders, Municipalities, and the Environment such as:

- The reduction of land clearing and grading costs;
- Balancing the need for growth and environmental protection;
- The protection of local land and water resources.

LID utilizes a system of source controls and small-scale, decentralized treatment practices to help maintain a hydrologically functional landscape. The conservation of open space, the reduction of impervious surfaces, and the use of small-scale storm water controls, such as bioretention, are just a few of the LID practices that can help maintain predevelopment hydrological conditions.

## Featured case study

Somerset is an 80-acre development in suburban Maryland consisting of 199 homes on 10,000 square foot lots. During Somerset's creation, the developer used LID practices to reduce its storm water management costs. By using LID, the developer:

- Eliminated the need for storm water ponds by using bioretention techniques saving approximately $300,000;

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For more information, download copies of the Builder's Guide to Low Impact Development and Municipal Guide to Low Impact Development brochures.

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ToolBase Services
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Upper Marlboro, MD 20774

# CAUSES OF SPRAWL: A PORTRAIT FROM SPACE*

MARCY BURCHFIELD
HENRY G. OVERMAN
DIEGO PUGA
MATTHEW A. TURNER

We study the extent to which U. S. urban development is sprawling and what determines differences in sprawl across space. Using remote-sensing data to track the evolution of land use on a grid of 8.7 billion 30 × 30 meter cells, we measure sprawl as the amount of undeveloped land surrounding an average urban dwelling. The extent of sprawl remained roughly unchanged between 1976 and 1992, although it varied dramatically across metropolitan areas. Ground water availability, temperate climate, rugged terrain, decentralized employment, early public transport infrastructure, uncertainty about metropolitan growth, and unincorporated land in the urban fringe all increase sprawl.

## I. INTRODUCTION

In a recent survey by the Pew Center for Civic Journalism [2000], 18 percent of Americans said urban sprawl and land development were the most important issue facing their local community—the top response, tied with crime and violence. However, there was a key element of disagreement. Respondents to this survey were almost evenly split (40 versus 52 percent) between those wanting local government to limit further development to the infilling of already built-up areas and those wanting local government also to allow more scattered development in previously undeveloped areas. Despite this widespread interest,

* For helpful comments and suggestions we thank three anonymous referees, William Fischel, Masahisa Fujita, John Hartwick, Vernon Henderson, John Landis, William Strange, and, in particular, Edward Glaeser. We also received helpful comments from seminar participants at the University of California Berkeley, Harvard University, Universitat Pompeu Fabra and Stanford University, and at conferences organized by the Regional Science Association International, the Centre for Economic Policy Research, the Association of Environmental and Resource Economists, and the Lincoln Institute. We are very grateful to Ferko Csillag for his advice on remote-sensing data. Also to the U. S. Geological Survey, and in particular to Stephen Howard and James Vogelmann, for early access to preliminary versions of the 1992 data. Vernon Henderson and Jordan Rappaport kindly provided us with data on metropolitan population 1920–1990, Matthew Kahn with data on employment decentralization, and Jacob Vigdor with data on streetcar usage. Kent Todd helped with ARC Macro Language scripts. While working on this project, Burchfield was an Master's student at the Department of Geography, University of Toronto. Funding from the Social Sciences and Humanities Research Council of Canada (Puga and Turner) and from the Centre de Recerca en Economia Internacional and the Centre de Referència d'Economia Analítica (Puga), as well as the support of the Canadian Institute for Advanced Research (Puga) and the National Fellows program at the Hoover Institution (Turner) are gratefully acknowledged.


*The Quarterly Journal of Economics*, May 2006

spatial development patterns are the dimension of sprawl that we know the least about. We have some understanding of what determines urban growth (see, e.g., Glaeser, Scheinkman, and Shleifer [1995], Overman and Ioannides [2001], and Black and Henderson [2003]) and the decentralization of economic activity within cities [Glaeser and Kahn 2004]. However, we know almost nothing about the extent to which development is scattered or compact, how this varies across space or what determines that variation. This paper is concerned with this key aspect of sprawl.

Existing data sets are not well-suited for studying the scatteredness of development. To improve our understanding, we construct a new data set by merging high-altitude photographs from around 1976 with satellite images from 1992. From these data, for units that are square cells of 30 × 30 meters, we know whether land was developed or not around 1976 and in 1992, as well as details about the type of developed or undeveloped land. Our data set consists of 8.7 billion such 30 × 30 meter cells for a grid covering the entire conterminous United States.

Using these data, we provide basic facts about the extent of urban land development. Our main focus, however, is on the spatial patterns of residential land development—in particular, whether residential development is sprawling or compact. This involves capturing the extent to which residential development in urban areas is scattered across otherwise undeveloped land. In sprawling areas, much of the land immediately surrounding the average house will not itself be developed. Conversely, in areas where development is compact, there will be a high proportion of developed land in the immediate vicinity of the average house. To measure this, for each 30 × 30 meter cell of residential development, we calculate the percentage of undeveloped land in the immediate square kilometer. Averaging this measure across all *developed* cells in a metropolitan area gives us an index of sprawl for the metropolitan area: the percentage of open space in the square kilometer surrounding an *average* residential development. We calculate this index for all metropolitan areas and then examine the reasons why sprawl differs across space.

Regarding overall development, we find that only 1.9 percent of the United States was built-up or paved by 1992. Two-thirds of this was already in urban use by 1976, while the remaining one-third was developed subsequently. Turning to spatial patterns, only 0.3 percent of 1992 residential development is more than one kilometer away from other residential development. On the other hand, at a finer spatial scale, our measure of sprawl shows that 43 percent of the square kilometer surrounding an average residential development is undeveloped. Thus, while residential development almost never leapfrogs over large extensions of undeveloped land, it is also not particularly compact on average. Moreover, contrary to widespread claims, the extent to which average residential development is scattered was essentially unchanged between 1976 and 1992. That is, while we have seen an increase in the amount of residential development, that development was not any more biased toward sprawling areas in 1992 than in 1976. The same is not true of commercial development: this appears to have become considerably more biased toward sprawling areas in the time period under study. While spatial patterns of residential development did not vary much between 1976 and 1992, our sprawl index indicates that there are dramatic variations across metropolitan areas. Much of this paper is devoted to describing this variation and to investigating the ability of the various theories of urban economics to explain it.

We start with the monocentric city model and its generalizations. Consistent with these theories, factors that increase the importance of the central business district decrease sprawl. Thus, cities sprawl less if they specialize in sectors, such as business services, that tend to be centralized in the average city. The commute to the city center also plays a role, with cities built around public transportation more compact than cities built around the automobile. Patterns of past growth in the metropolitan area also affect sprawl. Cities with higher historical population growth rates sprawl less. Among other things, in fast growing cities small undeveloped plots do not stay undeveloped for long. Greater historical uncertainty about growth also causes more sprawl as developers withhold land to better adapt it to future needs.

We next consider physical geography. Despite technological progress, the physical environment continues to play an important role in shaping cities. Sprawl increases substantially with the presence of water-yielding aquifers in the urban fringe: such aquifers allow people to sink a well and locate far from other development without bearing the large costs of extending municipal water lines. Regarding physical barriers to development, high mountains close to development constrain urban expansion and tend to make development more compact. Hills and small-scale terrain irregularities, on the other hand, encourage scattered development. Finally, factors that increase the value of open space, a temperate climate in particular, increase sprawl. In all, physical geography alone explains about 25 percent of the cross-city variation in our sprawl measure.

We turn finally to political determinants of sprawl. There is more sprawl in cities where a large proportion of undeveloped land lay outside of any municipality. In contrast, municipal fragmentation has no effect, suggesting that developers are often leapfrogging out of municipal zoning and building regulations altogether, rather than playing municipalities against each other. Public finance also plays an important role. There is more sprawl in places where larger intergovernmental transfers mean that local residents bear less of the cost of extending infrastructure to service new scattered development.

## II. Data and Methodology

We construct our core data from two fine-resolution data sets describing land cover and land use (i.e., the physical features that cover the land and what those features are used for) across the conterminous United States for the mid-1970s and the early 1990s. The most recent data set, the 1992 National Land Cover Data [Vogelmann, Howard, Yang, Larson, Wylie, and Driel 2001] classifies the land area in 1992 into different land cover categories mainly on the basis of Landsat 5 Thematic Mapper satellite imagery. The earlier data set, the Land Use and Land Cover Digital Data [U. S. Geological Survey 1990; U. S. Environmental Protection Agency 1994], derives mainly from high-altitude aerial photographs taken circa 1976.[1]

Despite the different technologies used to construct the two data sets, the processes are fundamentally similar. For the 1992 data, first-pass boundaries of contiguous areas with similar land cover are generated by grouping together contiguous cells with similar vectors of reflectance values recorded by satellite imagery. Aerial photographs and ancillary data are then used to refine these boundaries and to assign land cover codes. For the 1976 data the initial boundaries are drawn directly on the basis of the aerial photographs, and then these photographs and ancillary data are used to assign land cover codes. While the 1970s data

1. These photographs were collected over the period 1971–1982, but the most common date is 1976, which is also the median year.

have been available for over a decade, the 1990s data only became available in 2001 and are the most current land use data available for the nation. The Data Appendix describes in more detail the process followed by the U. S. Geological Survey (USGS) and the U. S. Environmental Protection Agency (EPA) to construct each of the data sets, as well as the way in which we have completed and integrated them. Our resulting data set has units of observation which are square cells of 30 × 30 meters situated on a regular grid. For each of the approximately 8.7 billion cells that make up the conterminous United States, we know the predominant land cover and land use circa 1976 and in 1992. Land is categorized as residential development; commercial and industrial development and transportation networks; water; bare rock and sand; forest; range and grassland; agricultural land; or wetlands.

Figure I presents a map of the United States derived from our data. This map shows, in yellow, the stock of land that was already built up circa 1976, and in red, new urban land built between circa 1976 and 1992. Land that remained nonurban in 1992 appears gray with shaded relief, and water is marked blue. This map reveals a number of noteworthy aggregate features. Perhaps the most striking is that the United States is overwhelmingly unoccupied. In fact, our data show that only 1.9 percent of the land area was either built up or paved by 1992. Two-thirds of this developed land was already in urban use around 1976, one-third was developed subsequently. Developed area grew at a very high rate (2.5 percent annually, 48 percent over sixteen years), but new development absorbed only a very small proportion of undeveloped land (0.6 percent over sixteen years).[2]

Our estimate that only 1.9 percent of the United States was developed by 1992 is slightly lower than previous estimates. Typically, these estimates use the partition of the territory into "urban" and "rural" made by the U. S. Census Bureau for administrative purposes. In the 1990 census, 2.5 percent of the conterminous United States was classified as urban. Using this figure systematically overstates the extent of built-up land in population centers by counting the entire area as developed when it need not be. At the same time it ignores development housing the

2. Our data also allow us to look at the development rate of different types of undeveloped land. There is no large bias toward the development of any particular type of land.


FIGURE I
Urban Land in the Conterminous United States

one-quarter of the population that was classified as rural in 1990. Some recent studies (e.g., Fulton, Pendall, Nguyen, and Harrison [2001]) estimate built-up land using National Resource Inventory (NRI) data, assembled by the U. S. Department of Agriculture on the basis of remote-sensing data for a relatively small sample of U. S. nonfederal land. According to these data, 2.9 percent of the United States was urban or built-up by 1992. The main reason why this estimate is larger than our figure is that, in the NRI data, the boundaries of urban and built-up areas are drawn in such a way that they incorporate substantial amounts of undeveloped land. In particular, all undeveloped land located between buildings or roads that are up to 500 feet (152 meters) apart is classified as built-up [U. S. Department of Agriculture 1997]—contrast this with our 30-meter resolution. However, the main advantage of our data is that it allows us to measure the scatteredness of development, the key concern of this paper. In contrast, neither census urban/rural boundaries nor the NRI allows this; in fact, the NRI is not available at the substate level since "[data at the county level] do not meet NRI reliability standards because of the small sample sizes for geographic units of that size" [U. S. Department of Agriculture 2001, p. 21].[3]

While our data show that only 1.9 percent of all land was developed by 1992, this aggregate number masks large differences across states. Data for individual states are reported in Table I. The first two columns show the percentage of all land in each state that was urban by 1992 and by 1976. The third column reports the percentage of 1976 nonurban land converted to urban between 1976 and 1992. The last three columns report the percentages accounted for by each state of U. S. urban land in 1992, of U. S. land area, and of U. S. 1976 nonurban land converted to urban between 1976 and 1992.[4] One particularly interesting aspect of this heterogeneity is that coastal states both had high initial percentages of urban land and also experienced relatively fast growth. More detailed analysis shows that land within 80

3. A number of other papers use detailed geographical data similar to our own (e.g., Mieszkowski and Smith [1991], Rosenthal and Helsley [1994], Geoghegan, Wainger, and Bockstael [1997], Geoghegan [2002], and Irwin and Bockstael [2002]), but each focuses on a particular city or small area.

4. We correct for photographs not taken in 1976 by first determining the portions of each county photographed in any given year, then estimating the percentage of urban land in each of these county portions by assuming a constant local annual growth rate over the period, and finally aggregating up to the state and national levels.

TABLE I
THE EXTENT OF LAND DEVELOPMENT

| State | % of state's land area urbanized by 1992 | % of state's land area urbanized by 1976 | % of state's 1976 nonurban land urbanized 1976–1992 | State's % of U. S. urban land 1992 | State's % of U. S. land area 1992 | State's % of U. S. new urban land built 1976–1992 |
|---|---|---|---|---|---|---|
| Alabama | 1.39 | 1.02 | 0.37 | 1.24 | 1.71 | 1.01 |
| Arizona | 0.79 | 0.44 | 0.35 | 1.58 | 3.82 | 2.14 |
| Arkansas | 1.25 | 0.72 | 0.54 | 1.15 | 1.76 | 1.51 |
| California | 2.85 | 2.14 | 0.73 | 7.81 | 5.25 | 6.01 |
| Colorado | 0.89 | 0.49 | 0.40 | 1.62 | 3.50 | 2.25 |
| Connecticut | 16.30 | 9.89 | 7.12 | 1.38 | 0.16 | 1.67 |
| Delaware | 7.18 | 5.94 | 1.32 | 0.25 | 0.07 | 0.13 |
| DC | 68.13 | 67.21 | 2.80 | 0.07 | 0.00 | 0.00 |
| Florida | 8.93 | 4.45 | 4.68 | 8.52 | 1.83 | 13.10 |
| Georgia | 2.52 | 1.59 | 0.94 | 2.58 | 1.96 | 2.92 |
| Idaho | 0.39 | 0.19 | 0.20 | 0.57 | 2.80 | 0.89 |
| Illinois | 3.70 | 2.87 | 0.86 | 3.61 | 1.87 | 2.50 |
| Indiana | 3.38 | 2.60 | 0.80 | 2.14 | 1.21 | 1.52 |
| Iowa | 2.49 | 0.95 | 1.56 | 2.40 | 1.85 | 4.57 |
| Kansas | 0.98 | 0.67 | 0.31 | 1.41 | 2.76 | 1.37 |
| Kentucky | 1.84 | 1.33 | 0.52 | 1.29 | 1.35 | 1.11 |
| Louisiana | 2.62 | 1.80 | 0.84 | 1.99 | 1.46 | 1.92 |
| Maine | 1.41 | 0.96 | 0.45 | 0.76 | 1.04 | 0.74 |
| Maryland | 7.82 | 6.72 | 1.18 | 1.36 | 0.33 | 0.58 |
| Massachusetts | 17.34 | 12.35 | 5.70 | 2.42 | 0.27 | 2.13 |
| Michigan | 3.20 | 2.39 | 0.84 | 3.22 | 1.93 | 2.52 |
| Minnesota | 1.62 | 0.82 | 0.80 | 2.27 | 2.69 | 3.44 |
| Mississippi | 1.24 | 0.79 | 0.45 | 1.03 | 1.59 | 1.13 |
| Missouri | 1.95 | 1.24 | 0.72 | 2.38 | 2.33 | 2.65 |
| Montana | 0.21 | 0.10 | 0.11 | 0.55 | 4.92 | 0.90 |
| Nebraska | 0.60 | 0.41 | 0.20 | 0.82 | 2.61 | 0.82 |
| Nevada | 0.34 | 0.13 | 0.21 | 0.66 | 3.71 | 1.23 |
| New Hampshire | 4.56 | 2.49 | 2.12 | 0.64 | 0.27 | 0.89 |
| New Jersey | 20.57 | 17.78 | 3.39 | 2.54 | 0.24 | 1.06 |
| New Mexico | 0.34 | 0.22 | 0.12 | 0.72 | 4.06 | 0.75 |
| New York | 5.48 | 4.59 | 0.93 | 4.50 | 1.57 | 2.24 |
| North Carolina | 4.19 | 2.97 | 1.26 | 3.60 | 1.65 | 3.21 |
| North Dakota | 0.46 | 0.16 | 0.30 | 0.56 | 2.34 | 1.12 |
| Ohio | 5.27 | 4.41 | 0.90 | 3.80 | 1.38 | 1.90 |
| Oklahoma | 1.51 | 1.10 | 0.41 | 1.83 | 2.33 | 1.53 |
| Oregon | 0.76 | 0.53 | 0.23 | 1.27 | 3.21 | 1.17 |
| Pennsylvania | 4.13 | 3.37 | 0.79 | 3.23 | 1.50 | 1.83 |
| Rhode Island | 17.99 | 14.11 | 4.52 | 0.34 | 0.04 | 0.23 |
| South Carolina | 3.43 | 2.30 | 1.15 | 1.83 | 1.02 | 1.84 |
| South Dakota | 0.37 | 0.16 | 0.22 | 0.50 | 2.56 | 0.90 |
| Tennessee | 2.76 | 1.99 | 0.78 | 2.09 | 1.45 | 1.79 |
| Texas | 1.83 | 1.10 | 0.73 | 8.44 | 8.85 | 10.28 |
| Utah | 0.54 | 0.34 | 0.20 | 0.73 | 2.58 | 0.82 |
| Vermont | 2.91 | 1.47 | 1.46 | 0.30 | 0.20 | 0.45 |
| Virginia | 3.48 | 2.77 | 0.73 | 2.43 | 1.34 | 1.52 |
| Washington | 2.23 | 1.44 | 0.79 | 2.62 | 2.25 | 2.82 |
| West Virginia | 1.32 | 0.97 | 0.35 | 0.56 | 0.81 | 0.45 |
| Wisconsin | 1.84 | 1.28 | 0.57 | 1.77 | 1.84 | 1.65 |
| Wyoming | 0.21 | 0.11 | 0.09 | 0.36 | 3.28 | 0.49 |
| United States | 1.92 | 1.29 | 0.63 | 100.00 | 100.00 | 100.00 |

kilometers of the ocean or Great Lakes accounts for only 13.4 percent of the total land area, but contained 45.6 percent of developed land in 1976. This share declined slightly to 44.2 percent in 1992, but coastal areas still accounted for 41.3 percent of 1976–1992 urban development. Interestingly, the evolution of the coastal concentration was quite different for residential and commercial development. While the share of residential land within 80 kilometers of the coasts increased from 46.6 percent to 48.5 percent, the share of commercial land fell from 43.2 percent to 34.3 percent. The shift of commercial development away from coast is consistent with Holmes and Stevens' [2004] findings on changes in the location of large U. S. manufacturing plants. This decline in the coastal concentration of commercial land together with the rise in that of residential land can also be seen as supporting the argument made by Rappaport and Sachs [2003] that amenity considerations are increasingly important relative to production considerations in driving coastal concentration.

Zooming in, Figures IIa and IIb depict development for four areas: Atlanta (top of Figure IIa), Boston (bottom of Figure IIa), around San Francisco (top of Figure IIb), and around Miami (bottom of Figure IIb). As before, urban land circa 1976 is marked in yellow and 1976–1992 urban development in red, but nonurban land is now split according to its 1992 cover. These maps reveal some of the complex spatial details of the land development process. Atlanta, the epitome of sprawl, experienced an extraordinary amount of development from the mid-1970s and both recent and older development are very scattered. Boston had less recent development and contains a much more compact old urban core. However, the suburban development that took place since the mid-1970s is, by some measures, even more scattered than in Atlanta. Development in San Francisco and neighboring metropolitan areas is much more compact than in either Atlanta or Boston, although looking closely at the map one can see green speckles marking the presence of parks within the yellow-colored old development. New development respected these urban parks but remained contiguous to earlier development, as evidenced by the red on the fringe of pre-1970s development. Miami, like most of Florida, experienced spectacular growth in the amount of developed land, but unlike Atlanta, this recent development either infilled portions of undeveloped land within earlier development (notice there are fewer urban parks than in San Francisco) or took place contiguously with previously built-up areas. Figure III

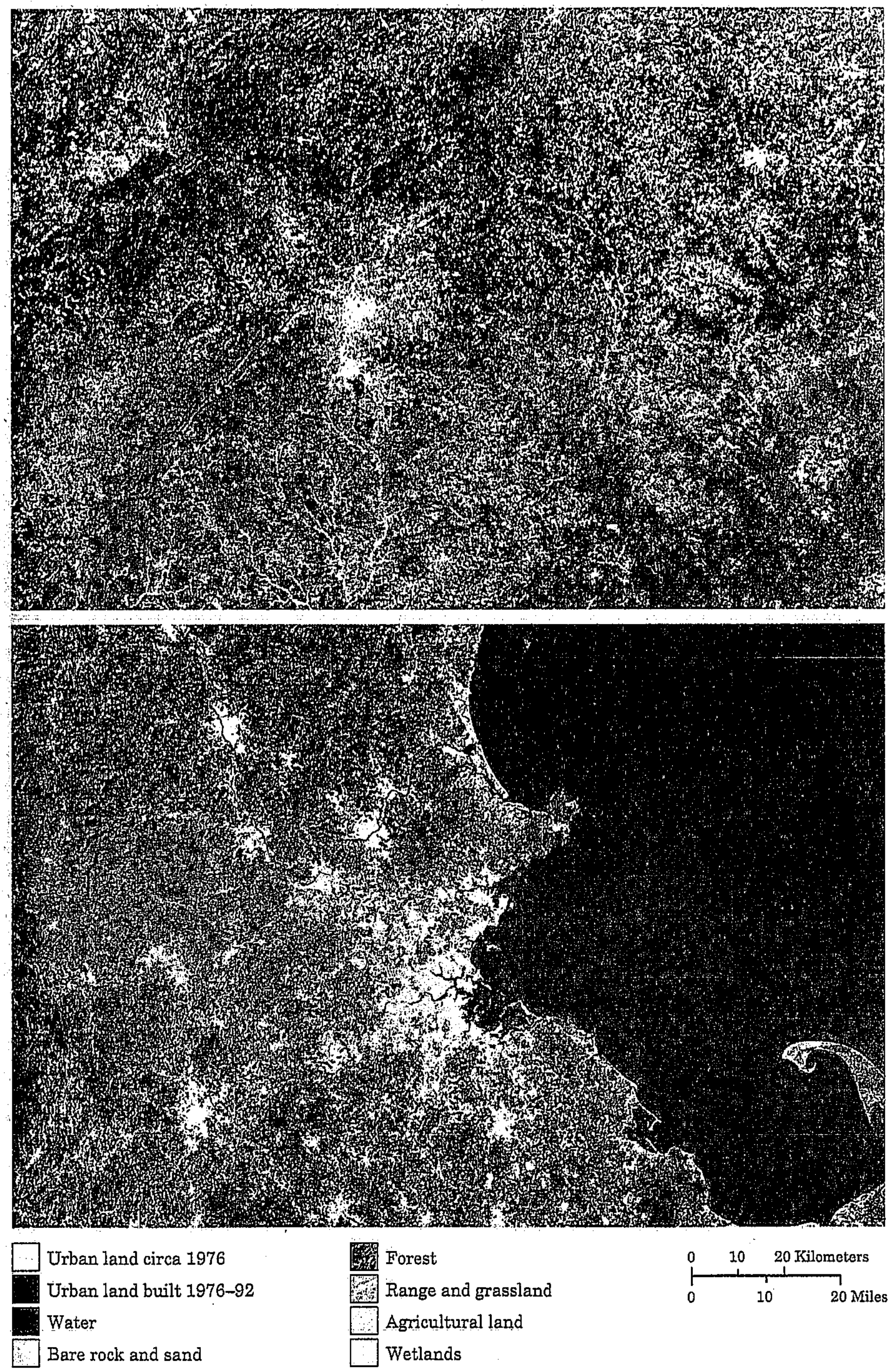


FIGURE IIa
Urban Land in Atlanta, GA (Top Panel) and Boston, MA (Bottom Panel)

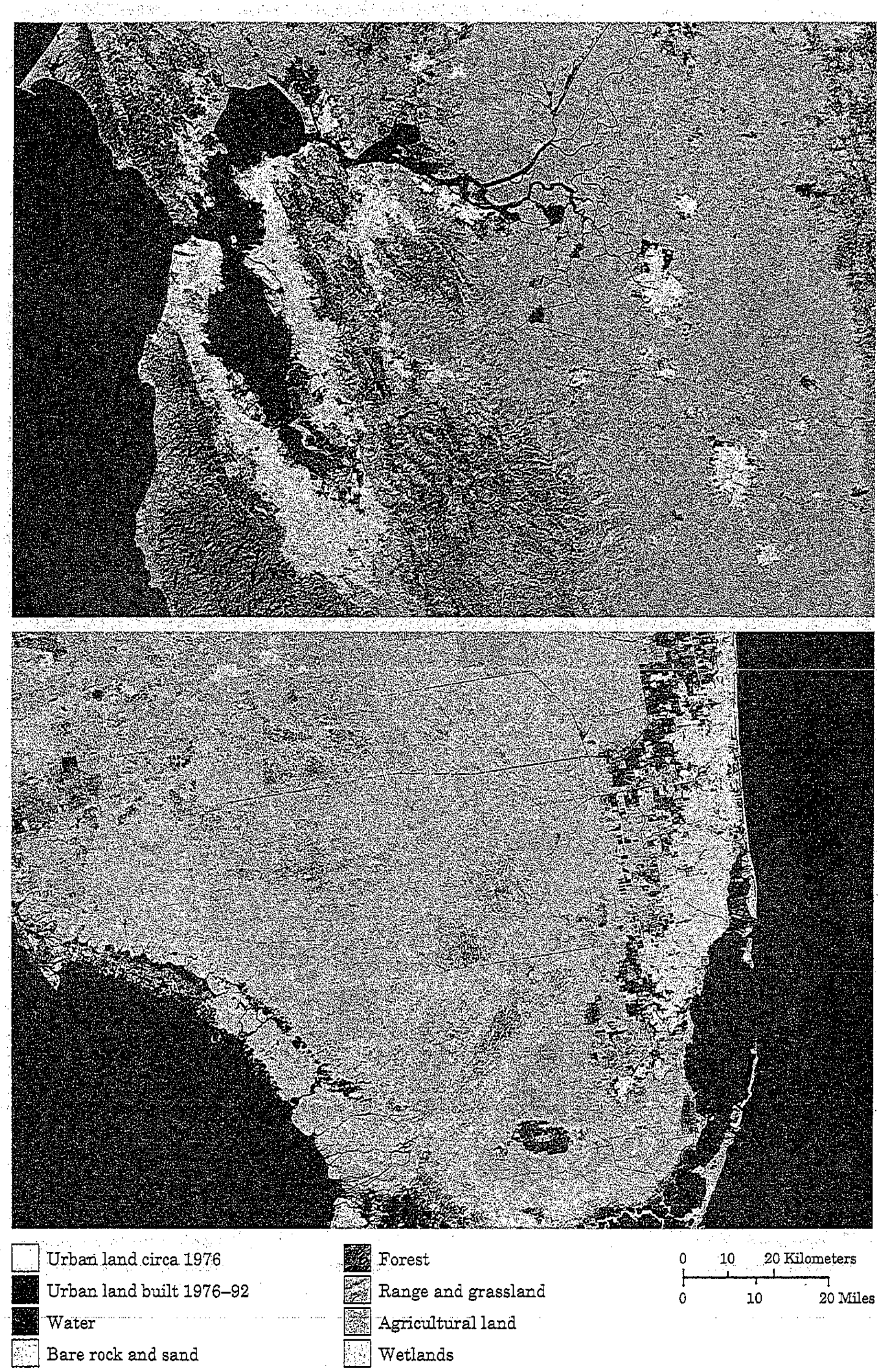


FIGURE IIb
Urban Land in San Francisco, CA (Top Panel) and Miami, FL (Bottom Panel)

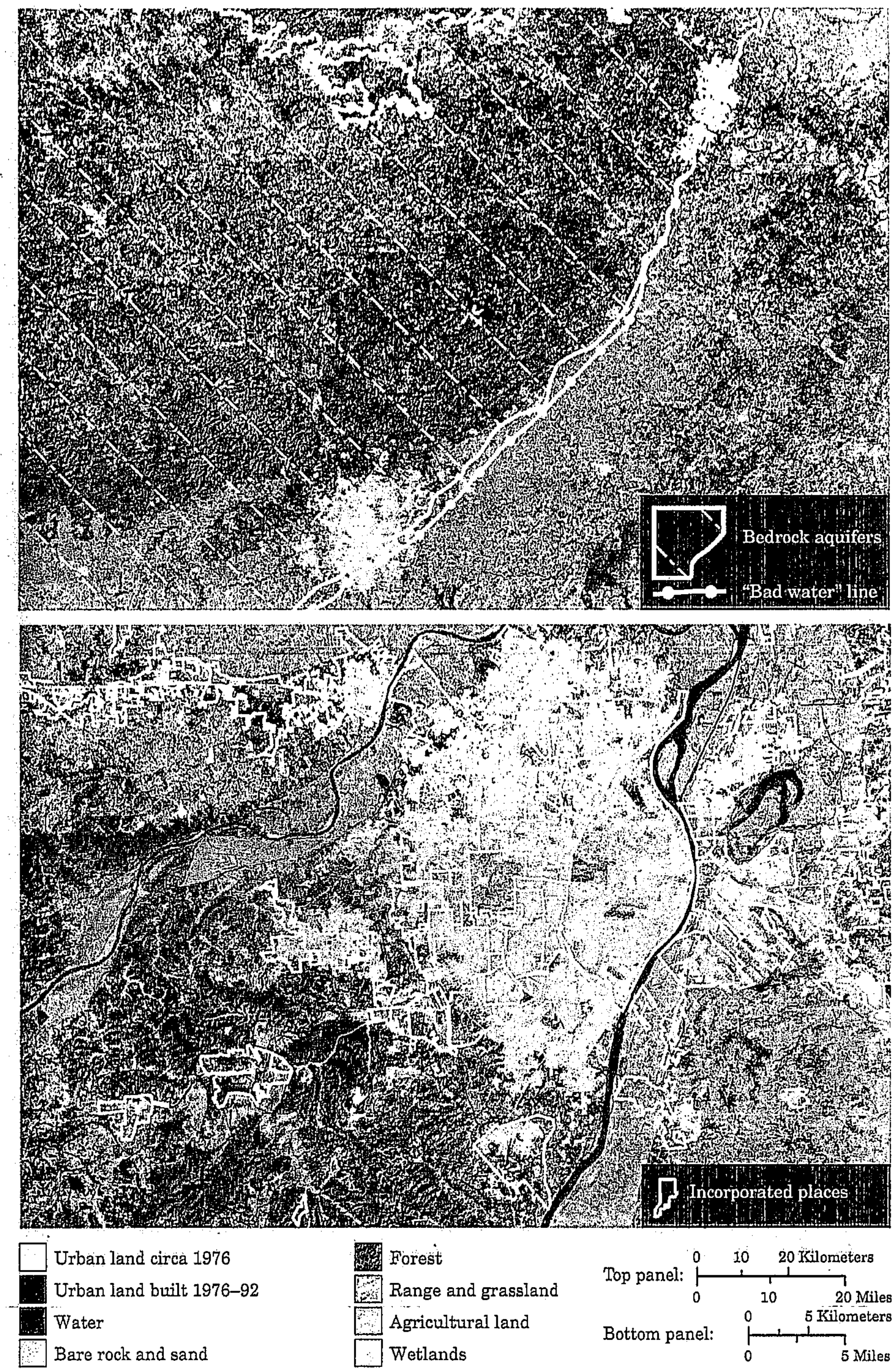


FIGURE III
Urban Land and Aquifers in San Antonio and Austin, TX (Top Panel), and Urban Land and Incorporated Places in Saint Louis, MO (Bottom Panel)

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presents two additional maps, depicting development in the area encompassing the Austin-San Marcos and San Antonio metropolitan areas (top panel, ignore for now the location of aquifers discussed later), and in the Saint Louis metropolitan area (bottom panel, drawn at a different scale to show details of the location of development relative to municipal boundaries, also discussed below). In terms of urban sprawl, these two areas are somewhere in between the scatteredness of Atlanta and Boston and the compactness of San Francisco and Miami.

To summarize such differences in the extent to which development is scattered or compact, we develop a measure of sprawl. The first step is to find a relevant spatial scale at which to conduct our analysis. To this end, we start by checking how often residential development leapfrogs over more than one kilometer of undeveloped land. It almost never does: only 0.3 percent of all residential development was more than one kilometer away from other residential development in 1992. Even for recent (1976–1992) development, the figure was only 0.5 percent.[5] Thus, if large amounts of development are scattered rather than compact, this is happening at spatial scales less than one kilometer. This means we need to exploit the full spatial resolution of our data and look within the immediate kilometer of development.

We proceed as follows. To measure the extent of sprawl, for each 30-meter cell of residential development, we calculate the percentage of open space in the immediate square kilometer.[6] We then average across all residential development in each metropolitan area to compute an index of sprawl. For instance, to calculate a sprawl index for the new development that took place between 1976 and 1992 in each metropolitan area, we identify 30-meter cells that were not developed in 1976 but were subject to residential development between 1976 and 1992, calculate the percentage of land not developed by 1992 in the square kilometer containing each of these 30-meter cells, and average across all such newly developed cells in the metropolitan area. We also

5. This tiny amount of long-distance leapfrogging has, however, significantly reduced peoples' ability to "get away from it all." The percentage of U. S. land more than five kilometers way from any residential development dropped from 58.1 percent in 1976 to 47 percent in 1992.

6. For computational reasons, rather than looking at the square kilometer centered on each 30-meter cell, we construct a grid made up of square blocks of 30-meter cells each measuring approximately one square kilometer (990 × 990 meter squares so that each one contains an integer number, 1089, of our underlying 30-meter cells). The percentage of open space is then calculated for the one-kilometer cell block in which each 30-meter cell is located.

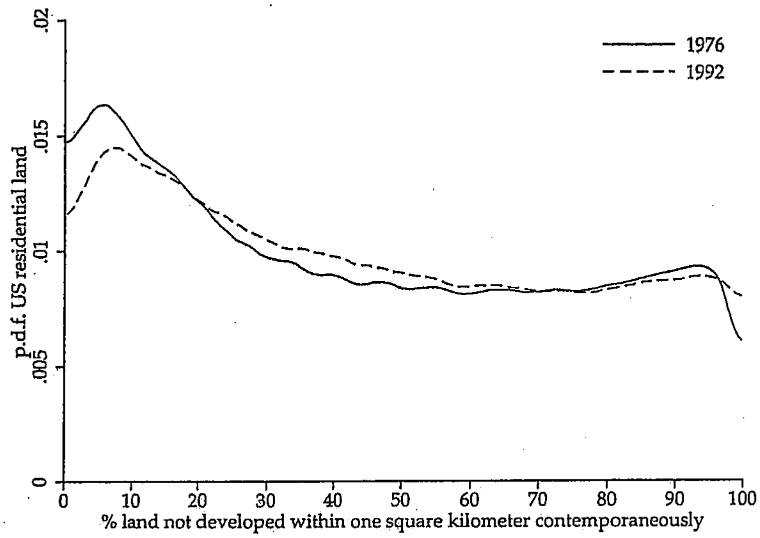


FIGURE IV
Probability Function of 1976 and 1992 U. S. Residential Land across Areas with Different Degrees of Sprawl

perform similar calculations to calculate a sprawl index for the stock of development in 1976 and in 1992. This provides a very intuitive index of sprawl: *the percentage of undeveloped land in the square kilometer surrounding an average residential development.*[7]

## III. SPRAWL ACROSS THE UNITED STATES

We start by examining the spatial structure of urban development for the United States as a whole. Figure IV plots the probability density function showing the distribution of residen-

7. One could imagine configurations of development for a particular square kilometer with a large percentage of open space that we might not want to characterize as sprawl. However, in metropolitan areas these are rare enough that they do not drive our sprawl index. In particular, since we average across all residential development rather than across all land in the metropolitan area, a square kilometer that is average for the nation at 43 percent undeveloped is counted 620 times (57 percent of 1089 cells) when averaging across the metropolitan area. On the other hand, a square kilometer with just one isolated developed cell is only counted once. Thus, the index is not driven by rare instances of isolated houses but by the groups of houses with an intermediate mixture of developed and undeveloped land surrounding them. For computational reasons, it is too difficult to work with buffers of less than one kilometer around houses. We have, however, tried other summary statistics, such as the percentage of undeveloped land in the square kilometer surrounding the median (instead of the average) residential development, and found almost identical results.

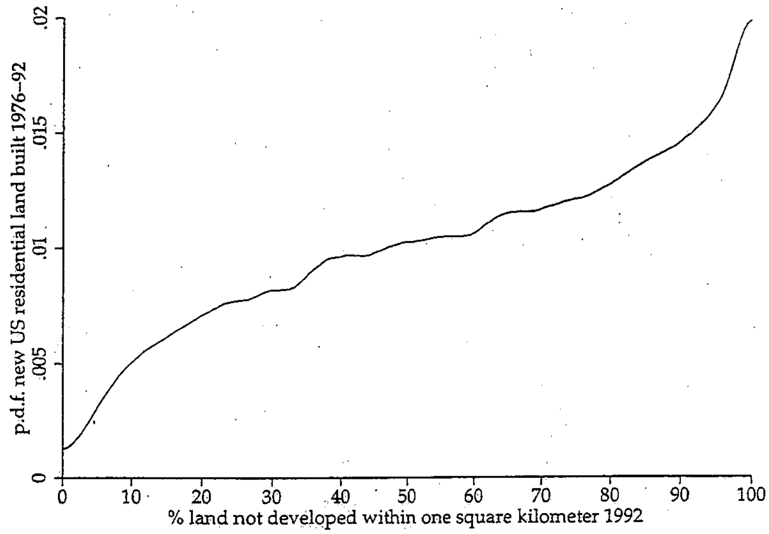


FIGURE V
Probability Function of 1976–1992 U. S. Residential Development across Areas with Different Degrees of Sprawl

tial development across areas with different degrees of sprawl. Consider the distribution for 1976, given by the solid line. The area under the line between any two values in the horizontal axis is the probability that a randomly picked 30-meter cell classified as residential development in 1976 lies in a square kilometer where the percentage of land not developed in 1976 lies between those two values. The figure shows that residential development was almost uniformly distributed across areas where between one-third and all of the surrounding square kilometer was not developed, but overall residential development was skewed toward more compact areas.

Figure V shows that this is not the case for new development that occurred between 1976 and 1992. The figure plots the probability density function for this new development across areas with different degrees of sprawl at the end of the period.[8] The figure shows that, in contrast to the stock of residential development in 1976, the flow of new residential development between

8. Note that is the amount of *final* development near new development that distinguishes sprawling from compact areas. The easiest way to see this is to consider a city that grows in a completely contiguous way. All new development occurs in areas that are initially almost entirely undeveloped but end up being completely developed.

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1976 and 1992 was biased toward sprawling areas. Thus, new development does tend to be scattered at small spatial scales.

We suspect that it is some perception that the flow of new development is more scattered than the initial stock that often leads people to conclude that development is more sprawled than in the past. However, looking back at Figure IV, we see that, for the dimension of sprawl that is our focus, this is not the case. The dashed line showing the distribution of the stock of 1992 residential development across areas with different degrees of sprawl is almost identical to the solid line for the 1976 stock. In fact, on average, 42 percent of the land in the square kilometer surrounding residential development was open space circa 1976. Remarkably, this figure remained almost unchanged at 43 percent in 1992. Thus, while a substantial amount of scattered residential development was built between 1976 and 1992, overall residential development did not become any more biased toward such sprawling areas.

To reconcile these apparently conflicting tendencies, note that the distribution of the final stock of development across different degrees of sprawl is *not* the result of adding the distribution of the flow of new development to the distribution of the initial stock. The reason is that, by adding the flow of new development to the initial stock, the distribution of the initial stock becomes shifted to the left as infilling makes formerly sprawling areas more compact. Figure VI further illustrates the importance of this infilling of areas that were partially developed to start with. It plots the average intensity of 1976–1992 residential development (i.e., the percentage of nonurban land turned residential) in areas with different percentages of open space in the immediate square kilometer in 1976. The figure shows that it is areas that were about half undeveloped in 1976 that were subject to the most intense subsequent residential development.

Pulling all this together, what do we learn about recent residential development and common perceptions of sprawl? It helps to consider how the environment might have changed near a hypothetical house located in a medium-density suburb. The open space in the immediate neighborhood of this house will most likely have been partly infilled. Areas initially more compact, presumably closer to downtown, will have experienced less change. Undeveloped areas farther out may now be scattered with low density development. To the family living in this house,

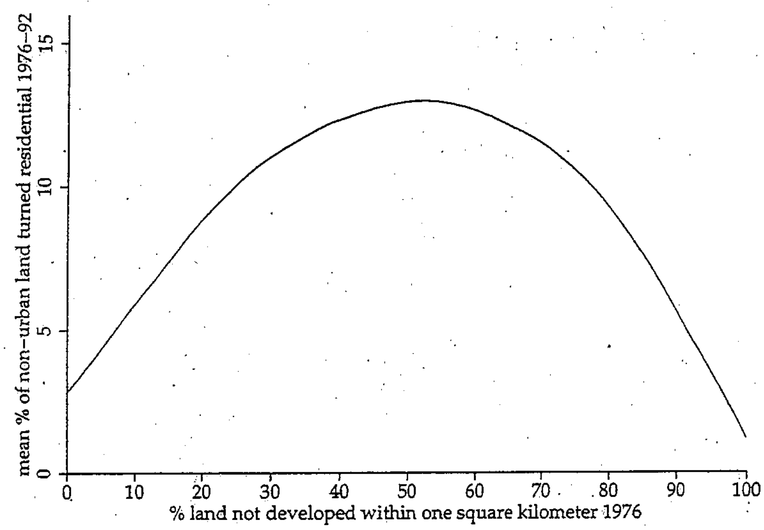


FIGURE VI
Mean Percentage of Nonurban Land Turned Residential 1976–1992 by Initial Percentage of Nonurban Land within One Square Kilometer

the pattern of residential development around them is very different from the one they experienced in the 1970s. However, if we zoom out and look at the city from a distance, we see little change, at least in the proportions of sprawling and compact development: the new city is just like an enlarged version of the old city.

While our focus is on residential sprawl, it is of interest to compare the distribution of residential land with that of commercial land. As it turns out, while the sort of places where Americans live has not changed substantially, the places where they shop and work has. Figure VII is a counterpart to Figure IV giving the distribution of commercial land (including industrial land and transportation networks) across areas with different percentages of developed land nearby. Looking first at the solid line, we see that the distribution for the stock of commercial land in 1976 is clearly bimodal. Commercial development in the 1970s was biased toward areas that were either very compact or very sprawling. Presumably the very compact commercial development is office buildings located downtown, while the scattered development is factories and malls located on the outskirts of town.

Turning to the dashed line in Figure VII, we see that, unlike residential land, commercial land has become more biased over

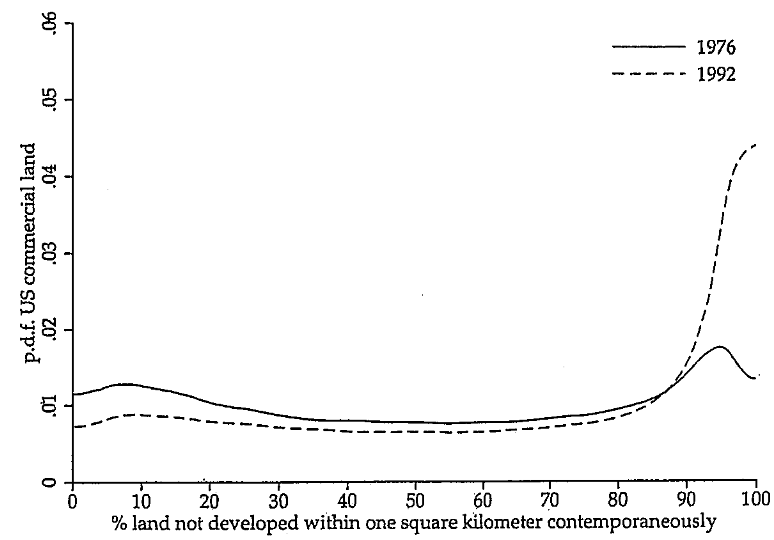


FIGURE VII
Probability Function of 1976 and 1992 U. S. Commercial Land across Areas with Different Degrees of Sprawl

time toward areas with little nearby development.[9] This finding is consistent with the view that the decentralization of housing in the United States had already reached its peak by the mid-1970s, whereas it is only more recently that employment, and especially manufacturing employment, has shifted from city centers to suburbia [Glaeser and Kahn 2001; Holmes and Stevens 2004].

### *III.A. Sprawling and Compact Cities*

Earlier in this section we showed that the distribution of U. S. residential development across areas with different degrees of sprawl remained almost unchanged between 1976 and 1992. Analogous distributions for individual metropolitan areas also show small differences across time for most areas but very large differences across areas at either point in time. We can summarize these differences using our sprawl index, the percentage of

9. It is worth noting that the proportions of residential and commercial land in overall U. S. urban land remained unchanged between 1976 and 1992 at about 70 percent and 30 percent, respectively. Hence, our findings do not reflect changes in the relative magnitudes of residential and commercial development but rather changes in their locations. We note that commercial land includes roads and industrial land, so this result may partly reflect new (or misdated) roads in rural areas as well as newly constructed factories and shopping malls. More detail on this issue is available in the Data Appendix.

TABLE II

SPRAWL INDICES FOR METROPOLITAN AREAS WITH POPULATION OVER ONE MILLION

| Metropolitan area | Sprawl index for 1992 residential land | Sprawl index for 1976 residential land | Metropolitan area | Sprawl index for 1992 residential land | Sprawl index for 1976 residential land |
|---|---|---|---|---|---|
| Atlanta | 55.57 | 57.77 | Minneapolis-St. Paul | 32.07 | 31.34 |
| Boston | 47.64 | 44.72 | New Haven | 39.11 | 38.68 |
| Buffalo | 39.92 | 37.87 | New Orleans | 32.29 | 33.92 |
| Charlotte | 52.73 | 51.12 | New York | 28.75 | 28.47 |
| Chicago | 31.76 | 31.21 | Norfolk | 40.82 | 44.07 |
| Cincinnati | 47.79 | 47.45 | Orlando | 40.02 | 39.39 |
| Cleveland | 36.84 | 36.24 | Philadelphia | 42.51 | 43.03 |
| Columbus | 41.20 | 41.59 | Phoenix | 27.54 | 34.94 |
| Dallas | 28.08 | 26.65 | Pittsburgh | 57.70 | 56.71 |
| Denver | 28.63 | 28.63 | Portland | 44.90 | 43.38 |
| Detroit | 33.28 | 30.47 | Rochester | 48.80 | 48.11 |
| Greensboro | 52.94 | 51.45 | Sacramento | 34.93 | 30.72 |
| Hartford | 41.34 | 42.23 | Salt Lake City | 31.90 | 32.88 |
| Houston | 38.15 | 38.93 | San Antonio | 32.77 | 29.58 |
| Indianapolis | 39.66 | 37.68 | San Diego | 45.63 | 45.40 |
| Kansas City | 35.32 | 34.33 | San Francisco | 30.48 | 29.81 |
| Los Angeles | 35.41 | 32.95 | Seattle | 46.97 | 45.03 |
| Memphis | 27.40 | 28.72 | St. Louis | 43.44 | 40.62 |
| Miami | 20.73 | 20.03 | Tampa | 36.01 | 34.84 |
| Milwaukee | 35.33 | 33.85 | Washington-Baltimore | 49.81 | 50.68 |

Each sprawl index measures the percentage of undeveloped land in the square kilometer surrounding an average residential development in each metropolitan area in the corresponding year (1992 or 1976). For instance, the sprawl index for 1992 residential land is computed by calculating the percentage of land not developed by 1992 in the square kilometer containing each 30-meter cell classified as residential land in 1992 and averaging this percentage across all cells classified as residential land in 1992 in the metropolitan area.

undeveloped land in the square kilometer surrounding an average residential development, which corresponds to the mean of these distributions. For each MSA with 1990 population greater than one million, Table II lists the sprawl index calculated for final (1992) and initial (1976) residential development.

A comparison of the figures provided in Table II with the maps presented in Figures IIa and IIb shows that the sprawl indices provide a good summary of development patterns. Overall development in Boston is substantially less scattered than in Atlanta, reflecting its much more compact old urban core (47.64 percent open space in the square kilometer around the average residential development in Boston in 1992, compared with 55–57 percent in Atlanta). However, the scatteredness of recent suburban development in Boston has made this metropolitan area somewhat less compact on average than it used to be: the percentage of undeveloped land around the average residential development increased from 44.72 to 47.64 between 1976 and 1992. Development in San Francisco is much more compact: only 30.48 percent of the square kilometer around the average residential development in San Francisco was not itself developed in 1992. Miami is even more compact than San Francisco, reflecting the greater presence of concrete and asphalt as opposed to small parks in between residential buildings: there was a mere 20.73 percent undeveloped land in the square kilometer around the average residential development in Miami in 1992.

Table II shows that, even at the metropolitan area level, the extent of sprawl is very stable over time. However, Table II also reveals the spatial heterogeneity of development patterns that is suggested by Figure I. The square kilometer around the average residential building in Atlanta or Pittsburgh is nearly 60 percent open space. In Miami this number is just over 20 percent. Before we turn to explaining this extraordinary variation across metropolitan areas, it is worth having a brief look at how our index compares with measures looking at alternative dimensions of sprawl.

### *III.B. Correlation with Other Measures of Sprawl*

Given that, until now, data to directly measure the scatteredness of development have been unavailable, median lot size has often been used as a proxy for metropolitan areas where this is known. We would expect places with a large median lot size also to have relatively scattered development as measured by our sprawl index, since residential developments built on larger lots tend to have a higher ratio of open space to built-up area. However, our index also captures the presence and size of undeveloped land in between built-up lots. Table III shows the correlation between our index for 1992 residential development and several other measures of sprawl for metropolitan areas with more than one million inhabitants in 1990.[10] The correlation between our index for 1992 residential development and median lot size in 1994–1998 is 0.52.

The scatteredness or compactness of residential development, while an important dimension of sprawl, is not the only

10. For most smaller metropolitan areas data are not available for these alternative indices. Correlations reported in Table III are for the largest 40 metropolitan areas listed in Table II (with the exception of median lot size which is based on 38 out of 40). See the Data Appendix for further details.

TABLE III
CORRELATION MATRIX FOR VARIOUS METROPOLITAN AREA SPRAWL MEASURES IN THE 1990S

| | Sprawl (scatteredness) index | Median lot size | Miles driven per person | % Employment over 3 miles from CBD |
|---|---|---|---|---|
| Sprawl (scatteredness) index | 1.000 | | | |
| Median lot size | 0.521 | 1.000 | | |
| Miles driven per person | 0.271 | 0.187 | 1.000 | |
| % Employment over 3 miles from CBD | −0.070 | 0.011 | −0.073 | 1.000 |

The sprawl (scatteredness) index is the measure of sprawl used throughout this paper: the percentage of undeveloped land in the square kilometer surrounding an average residential development in each metropolitan area in 1992. Median lot size compiled from the metropolitan data contained in the American Housing Survey 1994–1998. Average number of miles driven per person calculated from the 1995 Nationwide Personal Transportation Survey [U. S. Federal Highway Administration 1995]. Share of employment located more than three miles away from the central business district in 1996 from Glaeser and Kahn [2001].

one. "Sprawl" is also used to describe cities where people need to drive large distances to conduct their daily lives, or cities where employment is very decentralized [Glaeser and Kahn 2004]. People in more scattered metropolitan areas do tend to drive longer distances: the correlation between our index and the average miles driven per person is 0.27. However, there is almost no correlation between the extent to which residential development is scattered and that to which employment is decentralized (measured by the share of employment located more than three miles away from the central business district, as calculated by Glaeser and Kahn [2001]). This low correlation between measures of employment decentralization and other measures of sprawl is also noted by Glaeser and Kahn [2004].

These correlations are of interest for three reasons. First, because they highlight the complexity of spatial patterns of development. Second, they indicate the importance of interpreting our results appropriately. We determine the factors that lead to sprawl in the sense of scattered development. There is no reason to think that these factors will also explain the other features of the spatial patterns of development, such as how much people drive or the extent to which employment is decentralized. Finally, the table points out the difficulty of interpreting composite sprawl indices (e.g., Ewing, Pendall, and Chen [2002]). Given the low correlations between measures of different aspects of sprawl, when these are combined into a single number it is hard to know what is measured, let alone explain its determinants.

## IV. Urban Economic Theory and the Causes of Sprawl

To investigate the determinants of sprawl, we turn to urban economic theory for guidance. Unfortunately, there is no unified model that tells us what determines the extent to which development is scattered or compact. Instead, the difficulties involved in working with general equilibrium models where space is explicitly modeled have led urban economists to develop many special models to tackle particular issues. A few of these models have been written specifically to study some aspect of sprawl. Most of them have, however, been written with a different purpose in mind, yet also have implications relevant for sprawl. In this section we survey this literature in order to formulate hypotheses about the causes of sprawl.

### *IV.A. The Monocentric City Model and Its Generalizations*

The most widely used theoretical construct in urban economics is the monocentric city model, which deals with the determinants of variations in the intensity of residential urban development. This model derives from the pioneering contributions of Alonso [1964], Mills [1967], Muth [1969], and Wheaton [1974] (see Brueckner [1987] for an elegant synthesis). The monocentric city model assumes that all employment in the city takes place at a single center, the central business district. Residential development around that center is then shaped by the trade-off between convenient commuting close to the center and affordable housing farther away. Equal utility across residential locations implies that housing prices decline with distance to the city center to offset higher commuting costs. Equal profits for developers, who combine land and capital to produce housing, imply a similar gradient for land prices. Substitution in response to declining land and housing prices leads to larger dwellings with lower capital to land ratios (i.e., less tall, more spacious units and larger yards) as one moves away from the center.

The extent to which U. S. metropolitan areas can be characterized as monocentric has declined over time. The proportion of jobs located in central cities fell from about 75 percent in 1950 to about 45 percent in 1990 [Mieszkowski and Mills 1993], and metropolitan areas have become increasingly polycentric [Anas, Arnott, and Small 1998]. Beginning with the contributions of Fujita and Ogawa [1982] and Imai [1982] and continuing more recently with Lucas and Rossi-Hansberg [2002], a number of papers have extended the monocentric city model to endogenously derive monocentric as well as polycentric urban structures. In these models, cities specializing in sectors with stronger agglomeration economies, due to externalities in the transmission of information, tend to be monocentric while those with weaker agglomeration economies are more likely to be polycentric (see Chapter 6 in Fujita and Thisse [2002]). In their study using ZIP-code employment data, Glaeser and Kahn [2001] show that the extent of employment decentralization does indeed vary widely both across cities and across sectors. In addition, sectors such as business services where communication is particularly important do tend to be more centralized. General equilibrium models of systems of cities building on Henderson [1974, 1987] also show that cities specializing in sectors with stronger agglomeration economies have more expensive land, which offsets the higher wages resulting from agglomeration economies. Substitution away from land then implies higher buildings with smaller units and yards, i.e., more compact development. Thus, a crucial implication of the monocentric city model is that *cities specializing in sectors where employment tends to be more centralized will be more compact.*

A second prediction arising from the monocentric city model is that *lower transport costs within a city will result in more dispersed development.* A greater ability to use the car for commuting not only reduces transport costs, but also eliminates the fixed costs associated with public transport [Glaeser and Kohlhase 2004]. Both these effects contribute to sprawl.

The standard monocentric city model thus predicts scattered development, due to large yards, in cities specialized in sectors where employment is less centralized and where it is easier to use a car. However, a key feature that the standard monocentric city model cannot explain is leapfrog development where parcels of land are left undeveloped while others farther away are built up. Urban economists have followed two strategies to extend the monocentric city model to account for equilibrium leapfrogging. The first is to assign an amenity value to public open space so that individuals may be willing to incur the additional commuting costs associated with locating farther away from the city center in order to have open space near their home. Scattered development then takes the form of equilibrium leapfrogging, where remote areas are developed before central areas and residential development is mixed with undeveloped parcels [Turner 2005]. An immediate implication is that characteristics that make public open space more attractive will increase sprawl. While the same is true about private open space, there is one important regard in which public open space differs from private: the control that the residential owner has over subsequent development. If moving is costly, the willingness to trade off commuting costs against access to public open space will depend on expectations of how long that space will stay undeveloped. In areas where population is growing fast, a rational agent anticipates that nearby vacant land will be developed sooner, and thus is not willing to incur large additional commuting costs to gain access to it. Thus, *cities that have been growing faster will tend to experience less sprawl.*

The second strategy that urban economists have followed to account for equilibrium leapfrogging is to consider dynamic urban models where housing is durable and redevelopment costly. The core argument is that it may be optimal to postpone development of certain parcels so that in the future they can be developed in a way that better suits contemporaneous needs [Ohls and Pines 1975; Fujita 1976; Mills 1981] (see Fujita [1983] and Brueckner [2000] for reviews]. Uncertainty is particularly interesting in this context. In a model with uncertainty, Capozza and Helsley [1990] argue that developers should delay development until the value of the built-up land compensates for, not just the value of land in the best alternative use plus conversion costs (as in Arnott and Lewis [1979]), but also the option value of not developing in the face of uncertainty. Bar-Ilan and Strange [1996] extend Capozza and Helsley [1990] to allow for the fact that there are often long lags between the decision to build and the completion of construction. In this framework, uncertainty about urban growth translates into greater rent uncertainty the farther away a parcel is from the city center. In the presence of construction lags, an increase in uncertainty can encourage some landowners to choose earlier development. Thus, when leapfrogging occurs, *leapfrogging is greater the greater the uncertainty about future urban growth.*

### *IV.B. When Space Is Not a Featureless Plain*

Urban economists typically explain the clustering of people on the basis of agglomeration economies. While there are many microeconomic foundations for such economies (see Duranton and Puga [2004] and Rosenthal and Strange [2004] for reviews), perhaps the simplest is the existence of large indivisible public facilities [Buchanan 1965]. One example of particular interest is municipal water systems. What makes these shared water systems different from other public facilities is that in certain locations there is an alternative individual provision not subject to the same indivisibilities.

Most households in the United States get their water through the nearest municipal or county water supply. Extending water systems to service new scattered development in the urban fringe requires substantial infrastructure investments, the cost of which is typically borne by developers through connection fees and ultimately reflected in housing prices. For instance, to finance part of the $127 million cost of a twenty-mile pipeline to suburban development in Denver's South Metro area, the East Cherry Creek Valley Water and Sanitation District decided to charge $24,000 to connect new homes[11]—about one-seventh of the contemporaneous median house value in the Denver metropolitan area.

In places where water-yielding aquifers are pervasive, developers can sink a well instead of connecting to the municipal or county water supply. Fifteen percent of households in the United States get their water from private household wells [U. S. Environmental Protection Agency 1997]. According to the National Ground Water Association [wellowner.org], the average construction cost of a private well is approximately $4500. Private wells are rarely used in areas subject to compact development partly because in these areas they are often unsafe, or disallowed, by municipal regulations and partly because infill development in compact areas is typically subject to low water connection fees given the large number of connections per mile of pipe. However, low-cost private wells can facilitate scattered development in the urban fringe provided there is an aquifer from which to pump out water.

The top panel of Figure III illustrates the relationship between aquifers and sprawl with a map of San Antonio (located in the southwest of the map) and Austin (northeast), in Texas. Only part of these cities overlies an aquifer—the Edwards-Trinity

11. "Suburbs plan $127 million water system," *Rocky Mountain News*, December 19, 2003.

aquifer system—outlined and crosshatched in white. Households southeast of the "bad water line" plotted as a white dotted line cannot safely draw water from a well. The San Antonio Water System charges developers one-time connection fees per dwelling unit that range from $500 in some central areas to $24,000 in an eastern suburb. However, developers building in areas overlying the aquifer can sink a well and avoid the water connection fee or even build in areas where a connection to the municipal supply is not available. The map shows that most new development in San Antonio since the mid-1970s (marked in red) has taken place above the Edwards aquifer and that this development is much more scattered than that which does not overlay the aquifer. Austin shows a similar pattern.

Urban models typically treat space as a featureless plain to better focus on economic mechanisms, particularly agglomeration economies. The presence of aquifers is a particularly interesting dimension of underlying heterogeneity in the physical landscape precisely because of the way it interacts with agglomeration economies: *wherever aquifers underly the urban fringe, household water can be obtained without the large increasing returns associated with public water systems and this facilitates scattered development.* We now turn to other features of the physical landscape that are likely to matter for sprawl.

Nature can also contain sprawl through physical barriers hindering urban expansion. For instance, the mountains bordering Los Angeles are often mentioned as the main barrier to further expansion of its sprawling suburbs, and this has led to the coining of the phrase "sprawl hits the wall" [Southern California Studies Center and Brookings Institution 2001].

In studying the effect on sprawl of mountains located in the urban fringe, we need to be careful to separate large-scale from small-scale terrain irregularities. This is because one would expect mountains and hills to have opposite effects. When an expanding city hits a mountain range, further scattered development in the urban fringe becomes very costly. This encourages infilling and leads to increasingly compact residential patterns. On the other hand, small-scale irregularities in the urban fringe presumably have the opposite effect. When terrain in the urban fringe is rugged, steep hillsides where development is more costly alternate with flat portions where development is less costly. Thus, *we would expect rugged terrain to naturally encourage* *scattered development*. In contrast, *high mountains in the urban fringe are likely to make development more compact*.

In our discussion of the monocentric city model and its extensions, we saw that characteristics that make open space more attractive are likely to encourage both larger yards and more frequent undeveloped parcels providing public open space. Thus, a third hypothesis related to the physical landscape is that *cities with a pleasant temperate climate experience more sprawl*.

*IV.C. Political Geography*

In his excellent book on the economics of zoning, Fischel [1985] devotes substantial attention to the political geography of zoning. There, he discusses a possible relationship between jurisdictional fragmentation and the restrictiveness of zoning: if a small number of municipalities dominate a metro area, they may exploit their monopoly power on behalf of incumbent residents to restrict the supply of land and increase property values. He concludes that such a relationship is unlikely to be of practical importance for three reasons. First, large jurisdictions also tend to internalize the pros as well as the cons of development (e.g., a large jurisdiction is more likely to house the construction workers building new residences as well as the neighbors trying to stop these). Second, there are few instances of areas with highly concentrated municipal structures in the United States. Third, legal and practical restrictions limit the ability of even very dominant jurisdictions to act as monopolists.

Rubinfeld [1978] and Katz and Rosen [1987], among others, stress differences between zoned and unzoned areas instead of competition between zoned areas of different sizes. These differences are illustrated in Figure III. This map of municipal boundaries in Saint Louis (outlined in white) is very similar to one included in Fischel's [1985] analysis, except that we add land use data. This reveals that the most striking feature is actually the different character of new development on incorporated versus unincorporated land. A disproportionate share of 1976–1992 development happens in unincorporated areas that were close to existing development but just beyond the municipal boundaries as they were circa 1980. This development is also more dispersed than that on incorporated land. Many other metropolitan areas show a similar pattern. There is a good reason for this: almost every zoning law includes the provision that whenever regulations differ, the most restrictive rules apply. In unincorporated areas, only county and state planning regulations generally apply, while incorporated places add their own zoning restrictions and growth controls. *To the extent that there are unincorporated areas on the urban fringe, developers can escape municipal regulation by building outside municipal boundaries, and this facilitates sprawl.*

Finally, in Tiebout's [1956] model, zoning is the means by which communities can limit and shape immigration and development to suit the cost structure of local public goods. If local public services are more costly when development is scattered, then aversion to scattered development should be less strong, and *sprawl should be more prevalent where local taxpayers pay a smaller share of local government expenses.*

## V. The Causes of Sprawl

Our review of the urban economics literature in the preceding section suggests that cities will sprawl more if

- they specialize in sectors where employment is not typically located close to the city center;
- they were built around the car rather than around public transport;
- they have experienced slow population growth;
- there is greater uncertainty regarding their future population growth;
- aquifers underlie a greater fraction of their urban fringe;
- they are not surrounded by high mountains;
- terrain in their urban fringe is rugged;
- their climate is temperate;
- they begin with substantial unincorporated areas on the urban fringe;
- local taxpayers pay a smaller share of local government expenses.

In this section we test these predictions by regressing our sprawl index for new development in individual metropolitan areas on initial metropolitan area characteristics. The dependent variable in our regressions is therefore the percentage of undeveloped land in the square kilometer around an average 1976–1992 residential development in each metropolitan area (i.e., we identify 30-meter cells that were not developed in 1976 but were subject to residential development between 1976 and 1992, calculate the percentage of land not developed by 1992 in the square kilometer containing each of these 30-meter cells, and average across all such newly developed cells in the metropolitan area). Figures for the 40 largest metropolitan areas are reported in the final column of Table II, although we will consider all U. S. metropolitan areas in our regressions.

We focus on this dependent variable because concerns about new development drive most of the public debate about sprawl. In addition, we wish to avoid the obvious endogeneity issues that would arise if we instead used as dependent variable our sprawl index for the 1976 or 1992 stocks of development. However, as we show later, results using the sprawl index for the stock of 1992 development are very similar.

The spatial units of observation are individual metropolitan areas (although, obviously our calculations of the sprawl index and various explanatory variables still need to use the full spatial resolution of our data). We use the Metropolitan Statistical Area and Consolidated Metropolitan Statistical Area definitions (New England County Metropolitan Area definitions for New England). Since these are county-based definitions, care is needed when measuring the initial characteristics of areas where new development might take place. This is particularly important in the western part of the country, where counties are sometimes very large and consequently metropolitan area boundaries are often drawn much less tightly around the developed portion of metropolitan areas than in the East. We therefore restrict calculations for geographical variables to the "urban fringe," defined as those parts of the metropolitan area that were mostly undeveloped in 1976 but are located within 20 kilometers of areas that were mostly developed in 1976.[12] Given that we isolate the urban fringe in this manner, it makes sense to start with fairly wide metropolitan area boundaries before we cut out areas far away from initial development. We therefore use 1999 definitions [U. S. Bureau of the Census 2000]. We include all 275 metropolitan areas in the conterminous United States in our regressions.

12. Mostly developed areas are those where over 50 percent of the immediate square kilometer was developed in 1976. The choice of twenty kilometers as a threshold was guided by visual inspection of maps showing the evolution of land use in all metropolitan areas. A buffer of twenty kilometers around areas that were already mostly developed in 1976 includes 98 percent of 1976 residential development and 99 percent of subsequent residential development in metropolitan areas.

TABLE IV
THE DETERMINANTS OF SPRAWL

| | Regression results | | | | Summary statistics | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | Mean | St. dev. |
| Centralized-sector employment 1977 | −1.270 (0.517)** | −1.194 (0.526)** | −0.922 (0.599) | −0.462 (0.489) | 22.65 | 1.14 |
| Streetcar passengers per capita 1902 | −1.723 (0.507)*** | −1.918 (0.553)*** | −1.762 (0.520)*** | −1.822 (0.535)*** | 21.53 | 62.54 |
| Mean decennial % population growth 1920–1970 | −6.072 (1.854)*** | −5.528 (1.839)*** | −6.241 (2.187)*** | −4.686 (1.367)*** | 24.54 | 22.42 |
| Std. dev. decennial % population growth 1920–1970 | 3.169 (1.315)** | 3.208 (1.210)*** | 3.419 (1.424)** | 2.482 (1.005)** | 15.72 | 23.42 |
| % of urban fringe overlying aquifers | 1.222 (0.473)*** | 1.090 (0.507)** | 0.945 (0.539)* | 1.720 (0.484)*** | 30.43 | 37.96 |
| Elevation range in urban fringe (m.) | −1.609 (0.946)* | −1.166 (1.023) | 0.914 (1.117) | −1.731 (0.815)** | 542.43 | 737.02 |
| Terrain ruggedness index in urban fringe (m.) | 1.252 (0.746)* | 1.267 (0.746)* | 1.108 (0.767) | 2.195 (0.741)*** | 8.84 | 10.10 |
| Mean cooling degree-days | −6.512 (1.562)*** | −5.415 (1.657)*** | −6.440 (2.359)*** | −6.157 (1.564)*** | 1348.43 | 923.13 |
| Mean heating degree-days | −4.986 (1.341)*** | −4.768 (1.381)*** | −3.051 (2.632) | −6.966 (1.360)*** | 4580.79 | 2235.66 |
| % of urban fringe incorporated 1980 | −1.363 (0.455)*** | −1.558 (0.451)*** | −1.708 (0.464)*** | −1.629 (0.422)*** | 5.21 | 5.05 |
| Intergov. transfers as % of local revenues 1967 | 1.075 (0.633)* | 1.070 (0.682) | 1.136 (0.679)* | 2.206 (0.596)*** | 37.17 | 10.65 |
| Bars and restaurants per thousand people | | 0.176 (0.783) | | 1.51 | 0.41 | |
| Major road density in urban fringe (m./ha.) | | −0.179 (0.698) | | | 0.87 | 0.36 |
| % population growth 1970–1990 | | −1.916 (0.910)** | | | 35.29 | 45.46 |
| Herfindahl index of incorporated place sizes | | −0.274 (0.652) | | | 0.32 | 0.26 |
| Latitude | | | −2.083 (2.731) | | 37.57 | 5.22 |
| Longitude | | | −5.221 (2.700)* | | −91.18 | 13.52 |
| Census division fixed effects | | | Included | | | |
| Constant | 111.375 (11.503)*** | 108.895 (11.870)*** | 90.467 (21.441)*** | 75.050 (10.907)*** | | |
| Observations | 275 | 275 | 275 | 275 | | |
| $R^2$ | 0.405 | 0.418 | 0.469 | 0.404 | | |

The dependent variable in columns (1), (2), and (3) is our sprawl index for 1976–1992 development, which has mean 64.51 and standard deviation 10.90. The dependent variable in column (4) is our sprawl index for 1992 development, which has mean 46.54 and standard deviation 10.82. The regressions are run for all 275 metropolitan areas in the conterminous United States. Coefficients give the impact on the index of a one-standard-deviation increase in the corresponding variable. Numbers in brackets report heteroskedastic-consistent standard errors. ***, **, and * indicate significance at the 1 percent, 5 percent, and 10 percent level, respectively.

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Results are reported in Table IV.[13] Column (1) reports our main specification. Columns (2) and (3) report results including additional variables and controls. Finally, column (4) repeats our main specification using the sprawl index for 1992 development rather than for 1976–1992 development as the dependent variable. To aid comparison across variables, we report standardized coefficients that measure the absolute change in the sprawl index for a one-standard deviation change in each independent variable.

### *V.A. The Monocentric City Model and Its Generalizations*

We begin by examining the link between employment centralization and sprawl. Examining the link directly using a measure of the extent to which employment is centralized in each metropolitan area is clearly problematic: ceteris paribus, more compact cities will have more centralized employment. To avoid this endogeneity problem, we instead measure the extent to which the city is specialized in sectors, such as business services, that in the *average* city tend to be very centralized. To be precise, our measure is the share of employment that would be located within three miles of the central business district if employment in each sector in that metropolitan area was distributed relative to the center as it is in the average metropolitan area. See the Data Appendix for further details on how this variable is calculated. Results are reported in column (1) of Table IV. A one-standard deviation increase in centralized-sector employment decreases the sprawl index by 1.270 points. We see that, consistent with the monocentric city model, cities are more compact if they specialize in sectors that tend to be more centralized in the average metropolitan area.

Peoples' choice of residence might be driven by their leisure activities as well as by their employment. If employment centralization tends to limit the amount of sprawl, perhaps centralized amenities could play a similar role? To examine this possibility,

13. Our sprawl index is bounded between 0 and 100, so one may worry about the validity of OLS estimation. However, the minimum (33.35) and maximum (88.47) values occurring in the data are sufficiently far from the boundary to suggest that this is unlikely to cause problems in practice. This is also reflected in the fact that the minimum (36.01) and maximum (79.05) predicted values lie comfortably within the boundaries. Finally, note that converting to a (0,1) index and running the regression using a logistical transformation only results in some marginal changes to the significance of the results but makes coefficients much harder to interpret.

we tried including various consumer amenity variables used in Glaeser, Kolko, and Saiz [2001], such as live performance venues per capita or restaurants and bars per capita. Results reported in column (2), which includes restaurants and bars per capita, are typical: amenities have no impact and yet including them does not change our results. This is reasonably intuitive. Restaurants and bars are not actually any more centralized than household appliance stores [Glaeser and Kahn 2001]. Performance venues are, but the frequency with which most people go to these is such that their availability might affect the choice of metropolitan area (as suggested by the results on population growth in Glaeser, Kolko, and Saiz [2001]) but not so much the choice of whether to live in a compact or a scattered neighborhood.

We now turn to our prediction that car-friendly cities sprawl more. Naturally, cities developed mostly after the advent of the automobile tend to be much more car-friendly than cities built before 1900 around public transit. We use the number of streetcar passengers per capita in 1902 (from Cutler, Glaeser, and Vigdor [1999]) as a proxy for a historical city center less friendly to car usage. Table IV shows that a one-standard deviation increase in 1902 streetcar usage decreases the sprawl index by 1.723 points.

In addition to the role played by the historical city center, the car-friendliness of a city may also depend on the road density in the urban fringe. Column (2) shows that such a measure (major road density in the urban fringe, calculated from USGS 1980 digital line graphs) has no impact on sprawl, and including it does not change the coefficient on streetcar passengers or other variables. Note that, while more roads may facilitate scattered development, scattered development leads to a less dense road network. Our results suggest that neither of these counteracting effects dominates in the cross section. Using roads early in the study period does not solve this problem since, as we saw earlier, cities with more compact new development tended to also have more compact development in the past.

The third of our predictions concerns the impact of expected population growth on sprawl. In areas where population is growing fast, a rational agent anticipates that nearby vacant land will be developed sooner and, consequently, is not willing to incur large additional commuting costs to gain access to this open space. Developers may expect that cities that have been growing relatively fast in the past will continue to do so in the near future. We therefore proxy expected future population growth using the metropolitan area's historical mean decennial percentage population growth for the five decades 1920–1970.[14] Historical population growth rates are indeed a good predictor of population growth between the 1970s and 1990s: the correlation between percentage population growth 1970–1990 and mean decennial percentage population growth 1920–1970 is 0.60. Results in Table IV show that areas that have historically seen high population growth rates do, indeed, see less sprawl. A one-standard deviation increase in the historical mean growth rate reduces the sprawl index by 6.072 points.

We interpret this result as telling us something about the value of open space. However, given that historical population growth rates are a good predictor of current population growth rates, this result would also be consistent with fast growing cities using all available land to accommodate their growing population. However, when we add actual 1970–1992 population growth (clearly endogenous, and only introduced as a robustness check) in column (2), we see that this does not explain our results. Faster contemporaneous population growth does make cities more compact, but historical population growth rates continue to have much the same impact on sprawl.

To test our fourth prediction that greater uncertainty regarding future city growth fosters sprawl, we similarly assume that developers consider future local population growth more uncertain in cities that have had more ups and downs in population growth rates over previous decades. Specifically, our measure of uncertainty is the standard deviation of decennial percentage population growth rates 1920–1970 (using the same population time series as above). The results in Table IV show that, as expected, higher uncertainty leads to more sprawl. A one-standard-deviation increase in the standard deviation of decennial population growth rates increases the sprawl index by 3.169 points.

### *V.B. When Space is Not a Featureless Plain*

We now turn to consider the impact of a range of geographical variables. We begin with the prediction that aquifers facili-

14. Constructing a historical series of population data for U. S. metropolitan areas on the basis of county population counts in each decennial census requires tracking changes in county boundaries over time. We did this using a revised version of the County Longitudinal Template of Horan and Hargis [1995] kindly provided to us by Vernon Henderson and Jordan Rappaport.

tate sprawl, by allowing developers to sink a well and avoid the high water connection fees often incurred by scattered development. Results presented in Table IV show that this is indeed the case. A one-standard-deviation increase in the percentage of the urban fringe overlying aquifers (see the Data Appendix for details on this variable) increases the sprawl index by 1.222 points.

We think this result is particularly interesting. Urban economists have long highlighted the importance of indivisible public facilities for agglomeration. However, it is difficult to cleanly identify a role for indivisible public facilities in determining the extent to which development is clustered. Two particular features of water systems help us make a clean identification. First, we can detect their impact in the cross section because certain places (those with aquifers) have an alternative private provision that *is not* subject to the same indivisibilities. Second, the availability of this alternative provision through aquifers is certainly exogenous. This has some interesting policy implications that we consider in the conclusions.

What about terrain? We predict two effects from natural barriers and terrain ruggedness that should work in opposite directions. Coming up with a measure of the presence of mountains in the urban fringe is straightforward. For instance, we can calculate the range in elevation (i.e., the difference between the minimum and the maximum elevation) in the urban fringe. Measuring small-scale terrain irregularities, however, is more difficult because it requires much more geographically detailed elevation data. Given that readily available elevation grids covering the conterminous United States do not have the required spatial resolution, we have assembled a national elevation grid providing the elevation in meters of points 90 meters apart (see the Data Appendix for more detail). Using these data, we calculate the *terrain ruggedness index* originally devised by Riley, DeGloria, and Elliot [1999] to quantify topographic heterogeneity that can act either as concealment for prey or stalking cover for predators in wildlife habitats. This terrain ruggedness index, calculated on the 90-meter elevation grid, gives us a summary statistic of differences in meters of elevation between points 90-meters apart. This captures small-scale topographic heterogeneity using a local counterpart to the global elevation range that we use to capture the presence of mountains.

Turning again to our regression results in Table IV, we see that both mountains and hills have the expected effects. A one-standard-deviation increase in the elevation range in the urban fringe decreases the sprawl index by 1.609 points. In contrast, more rugged terrain is associated with more sprawl. A one-standard-deviation increase in the terrain ruggedness index increases the sprawl index by 1.252 points.

There are other barriers to urban expansion that could in principle have a similar effect to that of mountains: in particular, proximity to wetlands, public land, or oceans. We have tried numerous measures of all of these in our regressions, and none of them matter empirically. In the case of wetlands and public lands, this is not too surprising. Wetland mitigation banking programs allow developers to build on wetland areas in exchange for financing the preservation or restoration of wetlands elsewhere. For public land, the Homestead Act of 1862 allowed settlers to easily acquire private ownership of public land. As a result, public lands are concentrated in those parts of the nation that have historically been least attractive for setting up a residence. The lack of impact of proximity to the Atlantic and Pacific Oceans, the Gulf of Mexico, and the Great Lakes is more surprising. We have tried hard to find evidence that proximity to these large water bodies reduces sprawl and found none. We conjecture that this is partly because oceans act both as a barrier and as an outdoor amenity: one cannot build on the ocean but proximity to the ocean makes open space more enjoyable. Furthermore, as illustrated by the map of Boston in the bottom panel of Figure IIa, a city can be bounded by the ocean on one side and still sprawl profusely on the other.

Our final prediction regarding the role of geographical variables is that characteristics that make open space less attractive should reduce sprawl. The two most obvious characteristics are whether the city has an extremely hot or cold climate. A standard measure of extreme heat is cooling degree days, a concept used by engineers to calculate the demand for air conditioning. Extreme cold can be similarly measured through heating degree days, used to calculate fuel demand for heating. We use mean annual cooling and heating degree days calculated from climatic normals for the period 1961–1990 (again, see the Data Appendix for more details). The results in Table IV show that both variables have the predicted effect. A one-standard-deviation increase in mean cooling degree days reduces the sprawl index by 6.512 points. While a one-standard deviation in mean heating days reduces the sprawl index by 4.986 points.

We have also checked whether other climatic variables, such as average precipitation, have an impact on sprawl and found no evidence that they do. Finally, we have examined whether sprawl is affected by other characteristics that may change the attractiveness of open space. Variables capturing the percentage of forest or various types of vegetation in the urban fringe have no significant effects. This is in accordance with the literature on the amenity value of vegetation, which finds very mixed results (see Irwin [2002]).

### *V.C. Political Geography*

We turn, finally, to the role that political geography plays in driving sprawl. Estimation results confirm Fischel's assertion that the relationship between jurisdictional fragmentation and the restrictiveness of zoning is unlikely to be of empirical importance. Using a digital representation of the municipal boundaries in effect at the time of the 1980 census [GeoLytics 2000], we have computed various measures of municipal dominance (the ratio of the size of the largest municipality in each metropolitan area to the combined area of other municipalities, a Herfindahl index of municipality sizes, and the inverse of the number of municipalities). Results reported in column (2) for the Herfindahl index are typical: none of these measures have a statistically significant relationship with sprawl when added to our specification.

While competition between zoned areas of different sizes does not appear to matter for sprawl, the differences between zoned and unzoned areas stressed by Rubinfeld [1978] and Katz and Rosen [1987] do. To study the extent to which sprawl is encouraged by unincorporated areas on the urban fringe, that allow developers to escape municipal regulation, we calculate the percentage of the urban fringe incorporated in 1980. Results in column (1) of Table IV show that a one-standard-deviation increase in the percentage of the urban fringe incorporated reduces the sprawl index by 1.363 points. In all, these results suggest to us that the failure of municipal and county governments to harmonize land use regulation is an important contributor to sprawl. Developers, it seems, are often leapfrogging out of municipal regulations altogether rather than playing municipalities against each other.

To examine our final prediction that sprawl increases when local taxpayers bear less of the cost of providing public services to scattered development on the urban fringe, we include the percentage of local government revenue that were transfer payments from other levels of government in 1967 [U. S. Bureau of the Census 1974]. Table IV shows that this variable has the expected positive effect on sprawl: a one-standard-deviation increase in the percentage of intergovernmental transfers in local revenues in 1967 increases the sprawl index by 1.075 points.

### V.D. *Physical Geography and Urban Sprawl*

Our paper is unusual in its emphasis on the role that physical geography plays in explaining sprawl. In fact, a regression including only our five geographical variables (capturing the role of aquifers, terrain, and climate) explains 23.5 percent of the variation in our sprawl index. As one might expect, several of these variables vary in a quite predictable manner as one moves across the country. To check the extent to which these variables may just capture spatial gradients in the degree of sprawl, column (3) of Table IV reports results when we include the latitude and longitude of the centroid of each metropolitan area as well as fixed effects for nine census regions. Three geographical variables (the two terrain variables and mean heating degree days) are no longer significant at the 10 percent level. Remarkably, our aquifers variable and cooling degree days remain significant. In addition, the impact of all variables not measuring physical geography are essentially unchanged, with the exception of specialization in centralized sectors.

It is worth noting that, while our paper focuses on the causes of sprawl, there is also some public interest in the consequences of sprawl. Studying such consequences empirically will require good instruments, and our physical geography variables seem natural candidates. We also note that our results are robust to a variety of other changes to the specification in addition to those discussed throughout this section. Our regressions include all U. S. metropolitan areas regardless of their size. If we include the initial population of each metropolitan area in our specification, this variable is not significant, and the rest of our results are not affected. Similarly, the inclusion of other insignificant variables, such as various measures of demographic structure, segregation, or historical voting patterns, do not change the robustness of any of the results we report here.

### V.E. *Stocks Versus Flows of Development*

We have seen in Section III that there is very high persistence in the extent to which individual metropolitan areas are either sprawling or compact. In fact, the correlation between the sprawl indices for the 1976 and 1992 stocks of development is 0.96. We might therefore expect the variables that explain how sprawling are the flows of new development to also explain the cross sectional variation in how sprawling is the stock of final (1992) or initial (1976) residential development. Column (4) shows that, with the exception of centralized sector employment, initial characteristics have exactly the same impact on the extent to which final development in the metropolitan area is sprawled. Results (not reported) are very similar for initial development and also do not change when explanatory variables calculated for the urban fringe are instead calculated for the entire metropolitan area.

## VI. Conclusions

As with many economic and social processes, a true understanding of the implications of urban sprawl can only come about through the study of both the positive and normative aspects of the urban development process. Much of the current debate has seen people rushing to address normative issues without first having a good understanding of the positive aspects. In contrast, in providing the first detailed description of the process of urban development and its determinants, our paper is quite clearly focused on improving our understanding of these positive aspects.

To summarize, 1.9 percent of the land area of the United States was developed by 1992. Two-thirds of this developed land was already in urban use around 1976, while the remaining one-third was developed subsequently. Our main findings are concerned with whether development is sprawling or compact. We measure sprawl as the amount of undeveloped land surrounding an average urban dwelling. By this measure, commercial development has become somewhat more sprawling during the study period, but the extent of residential sprawl has remained roughly unchanged between 1976 and 1992. In contrast to this stability over time, the extent of sprawl does vary dramatically across metropolitan areas.

We study the factors that determine these large differences across metropolitan areas. We find that sprawl is positively associated with the degree to which employment is dispersed; the reliance of a city on the automobile over public transport; fast population growth; the value of holding on to undeveloped plots of land; the ease of drilling a well; rugged terrains and no high mountains; temperate climate; the percentage of land in the urban fringe not subject to municipal planning regulations; and low impact of public service financing on local taxpayers.

We are some way away from being able to make firm policy recommendations, but our results do raise some interesting questions for policy in this area. Perhaps the most intriguing issue arises from the connection between aquifers and sprawl. Often the same aquifer will supply water both to municipal water systems and to individual private wells. Private incentives may push for scattered development over the aquifer, where one can sink a well and avoid connection fees to the municipal supply. However, such development may be costly for others, since concrete, asphalt, and other nonpermeable materials hinder the replenishment of the aquifer with rainwater. In such a context, raising impact fees may only worsen the problem. This raises the intriguing possibility that groundwater regulation may provide an important avenue through which policy makers can influence the form of urban development. Another interesting policy implication arises from the fact that disparities between municipal and county regulation are important causes of sprawl. Focus, so far, has been on the fragmented nature of local government, but our results suggest that harmonization of county and municipal land use regulation may actually play a much more important role in influencing the form of urban development. Interestingly, while we find that sprawl is affected by two factors which have received little attention, another (the density of roads) that has received much more attention seems to have little impact. While more car-friendly cities do experience more sprawl, we find that what really matters is not the density of the road network on the urban fringe but instead whether the city center was shaped before the advent of the car. Finally, our results on the transfer share in local revenues suggest that internalizing the fiscal externalities of new development appears to limit urban sprawl.

Of course, these comments are fairly speculative given the current state of our knowledge. Further analysis of economic models of development, and of models which incorporate a taste for landscape features is warranted, and such analysis should form the basis for future policy recommendations.

## Data Appendix

### A. Land Use/Land Cover Data

We construct our core data from two remote-sensing data sets. The most recent, the 1992 National Land Cover Data [Vogelmann et al. 2001] are derived mainly from leaves-off (spring/fall) and leaves-on (summer) 1992 Landsat 5 Thematic Mapper satellite imagery. The Earth Resources Observation Systems (EROS) data center of the United States Geological Survey (USGS) converted the raw satellite images to land cover categories. Here we give a brief overview of the process, described in detail in Vogelmann, Sohl, Campbell, and Shaw [1998], Vogelmann, Sohl, and Howard [1998], and Vogelmann et al. [2001].

The Thematic Mapper sensor on the Landsat 5 satellite records data for units that are square pixels of 30 × 30 meters on a regular grid. We refer to these units as 30-meter cells. The sensor detects electromagnetic radiation reflecting from the earth's surface in seven wavelength bands (four of which are used to construct the data). Combining reflectance information from different bands for each 30-meter cell allows a very precise distinction between land cover features because different types of land cover reflect different amounts of radiation at different wavelengths. For instance, healthy vegetation reflects infrared light to remain cool and wet but absorbs visible light for photosynthesis.

Land cover was classified as follows. First, a computer algorithm was used to find clusters of contiguous 30-meter cells with a similar set of reflectance values over the electromagnetic spectrum. Next, analysts used high-altitude aerial photographs and other census and remote sensing data to match these clusters to land cover classes, to refine the boundaries of these clusters, and to make finer distinctions between land cover classes. Since a single cell may contain multiple land cover types, categorization is based on thresholds. For instance, for a cell to be assigned an urban code at least 30 percent of it must be covered with constructed materials. Using this approach, each 30-meter cell was categorized into one of 21 land cover classes.

Like the 1990s data, the 1970s [U. S. Geological Survey 1990;

U. S. Environmental Protection Agency 1994] classify the conterminous U. S. land area into land use/land cover categories. However, rather than satellite imagery, the 1970s data derive mainly from high-altitude aerial photographs collected between 1971–1982. The most common date is 1976, which is also the median year. The conversion to land use/land cover data was done by the USGS. The U. S. Environmental Protection Agency (EPA) further processed the data to facilitate use in geographic information systems, and we use their version [U. S. Environmental Protection Agency 1994]. We filled gaps in these data to construct the first complete coverage for the conterminous United States.[15]

To construct the 1976 data, analysts studied the photographs and, with the help of ancillary data, traced the boundaries of contiguous areas with similar land cover and assigned one of 37 land cover codes. The rules for drawing these boundaries mean that areas may differ in size and that a single area may contain multiple land cover types. Thus, as before, categorization is based on thresholds. For instance, to be assigned an urban code an area must have at least 20 percent urban cover within 4 hectares (10 acres). The resulting data contain the digitized boundaries of these hand-drawn areas (irregular polygons) and a code describing the preponderant land cover for each of them. U. S. Geological Survey [1990] gives a more detailed description of this process.

While the 1976 and 1992 data are roughly comparable, there are a few differences with implications for our analysis. First, the 1992 data are stored in raster format (assigning a code to each cell on a regular grid) while the 1976 data are stored in vector format (assigning a code and providing coordinates for irregular polygons). They also have different geographical projections. Thus, we converted the 1976 data to the same projection and data

15. The digital version of the land use and land cover data from 1:250,000 scale maps produced by the USGS lacks data for a thirty-by-sixty minute rectangle in the map for Albuquerque and in the map for Cedar City and for a one degree by one degree square in the map for Tampa. For Albuquerque and Cedar City, the USGS had digitized data from the 1:100,000 scale maps corresponding to the rectangles with missing data (Chaco Mesa in the case of Albuquerque, and Kanab in the case of Cedar City). We processed these data with the same computer code used by the EPA for the rest of the nation to completely fill the gaps. For Tampa, the missing data were not available digitally but could be found in the corresponding 1:250,000 scale paper map distributed by the USGS. We digitized this to the same format specifications as the rest of the EPA data. Using the USGS paper and digital distributions of the data and two alternative sources for the EPA distribution, we were also able to correct various instances in which land use codes had become corrupted during processing stages that occurred before we received the data. The data used to fill the three holes in the USGS data are available from http://diegopuga.org/data/sprawl/.

model as the 1992 data, by breaking up each polygon into the 30-meter cells it contains. This yields a data set giving the preponderant land cover/land use of each 30-meter cell in a regular grid covering the entire conterminous United States circa 1976 and in 1992. The second difference is that the data are categorized using classifications with different degrees of detail. For this reason, we work with two urban codes that can be defined in both years: residential; and commercial, industrial, and transportation networks.

The third and most important difference arises from the fact that the 1976 data are slightly less precise than the 1992 data when identifying small features different from their surroundings. Given this, rather than compare the data directly, we use the 1976 data to separate urban land in 1992 into new and old development. Thus, we define old development as land that was classified as urban in both 1992 and 1976. We define new development as land that was classified as urban in 1992, but was not urban in 1976. This procedure largely corrects for the difference, but has the drawback that we cannot capture developed land that is converted to farmland, etc. However, such undevelopment is rare: calculations by the Department of Agriculture suggest that less than 0.8 percent of developed land was undeveloped over the fifteen-year period 1982–1997 [U. S. Department of Agriculture 2000].

One possible source of mismeasurement remains: we may date some development incorrectly, if it is small enough relative to the resolution of our data and different from its surroundings in at least one of the two periods. We cannot provide a precise upper bound on the magnitude of this misdating. However, careful inspection suggests that only one result might be sensitive to this: when we find that commercial development became more biased toward scattered areas, this result is amplified by the fact that land classified as commercial/industrial/transportation in 1992 occasionally includes small rural roads that were too small to register with the 1976 data.

### B. *Data for Alternative Sprawl Measures*

Median lot size was compiled from the metropolitan data contained in the American Housing Survey [U. S. Bureau of the Census 1994–1998]. The metropolitan data in the American Housing Survey cover 47 metropolitan areas, where a sample of householders are interviewed about every six years. Each year, data for a few metropolitan areas are gathered on a rotating basis until all 47 areas included are surveyed. The cycle then begins again. The American Housing Survey does not survey three metropolitan areas with populations over one million (Greensboro, New Haven, and Orlando), although in the case of Greensboro median lot size in 1995 is available from the City of Greensboro Planning Department 2003. Thus, we have median lot size data for 38 cities with populations over one million.

The average number of miles driven per person in individual metropolitan areas was calculated from the 1995 Nationwide Personal Transportation Survey [U. S. Federal Highway Administration 1995], using the tools to calculate local area statistics described in Reuscher, Schmoyer, and Hu [2001]. The share of employment located more than three miles away from the central business district in 1996 was kindly provided by Matt Kahn from Glaeser and Kahn [2001].

*C. Additional Data for the Determinants of Sprawl*

The following paragraphs provide details on data sources and construction for several variables used in our regressions. All data required to run these regressions are available from http://diegopuga.org/data/sprawl/.

*Centralized sector employment 1977:* For each metropolitan area, we use county business pattern data for 1977 to calculate the share of employment in each three-digit SIC sector $i$, $s_{MSA,i}$. For each sector we know from Glaeser and Kahn [2001] the mean percentage of metropolitan area employment in that sector that is found within three miles of the central business district, $\bar{s}_{3,i}$ (see their paper for details of the calculations). Our measure of centralization of employment is then calculated as $\Sigma_i s_{msa,i} \times \bar{s}_{3,i}$.

*Percentage of the urban fringe overlaying aquifers:* We use data from U. S. Geological Survey [2003], originally developed by the USGS to produce the maps printed in the *Ground Water Atlas of the United States* [U. S. Geological Survey 2000]. This contains the shallowest principal aquifer at each point of the United States in a continuous geographical coverage. We exclude shallow sand and gravel aquifers since their high permeability and shallow depth to the water table make them particularly susceptible to contamination from nitrates and other pollutants whose presence in sufficient quantity renders water unsuitable for human consumption [Burkart and Stoner 2002].

*Elevation range and Terrain Ruggedness Index in the urban* *fringe:* We assemble the national elevation grid by merging 922 separate elevation grids from the 1:250,000-scale Digital Elevation Models of the USGS, each of which provides 3-arc-second elevation data for an area of one by one degrees. Let $e_{r,c}$ denote elevation at the point located in row $r$ and column $c$ of a grid of elevation points. Then the Terrain Ruggedness Index of Riley, DeGloria, and Eliot [1999] at that point is calculated as $[\sum_{i=r-1}^{r+1} \sum_{i=c-1}^{c+1} (e_{i,j} - e_{r,c})^2]^{1/2}$. The variable used in the regression is the average terrain ruggedness index of the urban fringe in each metropolitan area.

*Mean cooling and heating degree days:* Our weather variables are calculated from the climatic normals for individual weather stations 1961–1990 contained in the *Climate Atlas of the United States*. Cooling degrees on a given day are zero if the average temperature is below 65°F (about 18°C) and the degrees by which the average temperature exceeds 65°F otherwise. Mean annual cooling degree days are computed by summing cooling degrees over all days in a year. Mean annual heating degree days are similarly calculated by summing degrees below 65°F over all days in a year. We computed metropolitan area mean cooling and heating degree days by averaging climatic normals over all reporting weather stations in each metropolitan area. For the four metropolitan areas that did not contain a reporting station, we averaged data from weather stations within 30 kilometers of the metropolitan area.

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# Effects of Urbanization on Stream Ecosystems

The National Water-Quality Assessment (NAWQA) Program of the U.S. Geological Survey (USGS) is investigating the effects of urbanization on stream ecosystems in 15 metropolitan areas. Assessments began in 1999 in the metropolitan areas of Anchorage, Alaska; Birmingham, Alabama; Boston, Massachusetts; Chicago, Illinois; Cincinnati-Dayton, Ohio; Los Angeles, California; Philadelphia, Pennsylvania; Trenton, New Jersey; and Salt Lake City, Utah. Additional studies began in 2001 in Atlanta, Georgia; Reno-Sparks, Nevada; Dallas-Fort Worth, Texas; Denver, Colorado; Raleigh-Durham-Chapel Hill, North Carolina; Milwaukee, Wisconsin; and Portland-Salem-Eugene, Oregon. In all of these studies, urbanization is defined as the conversion from rural land uses to residential and commercial uses that are typical of recent, generally sprawling, urban-growth patterns.

## Specific questions addressed by all studies

- As watersheds are urbanized, what is the magnitude and pattern of response in stream hydrology, water chemistry, and biological communities? Are there threshold levels of urbanization at which stream ecosystems degrade more rapidly?
- What watershed characteristics, such as basin slope, geology, and soils, are closely related to hydrologic, chemical, and biological responses to urbanization?
- How do biological responses to urbanization vary among the diverse environmental settings of these metropolitan areas?
- What are the susceptibilities of specific aquatic organisms to water-quality degradation caused by urbanization?
- What are the best measures to use for monitoring water quality in watersheds that are becoming increasingly urbanized?

## Preliminary findings

Data from the 1999 studies are being compiled and interpreted; findings will be reported in journals and USGS reports in 2003. Preliminary analysis indicates that:

- Rapid degradation of stream ecosystems occurs early in the process of watershed urbanization. For example, in Anchorage, invertebrate communities that are sensitive to pollution and habitat modifications declined when about 5 percent of land cover in the watershed was converted to "impervious area," such as roads, parking lots, and houses.
- Early, rapid degradation is associated with processes, such as deforestation, that alter hydrology, stream temperature, and habitat. In some areas, these physical factors severely degrade biological communities before nutrients and other contaminants from non-point sources reach concentrations that may further degrade the communities.
- The magnitude of stream ecosystem response generally is greater when forests or rangeland are urbanized than when agricultural areas planted in row crops are urbanized.

USGS biologists collecting fish for tissue analysis and community status assessment.

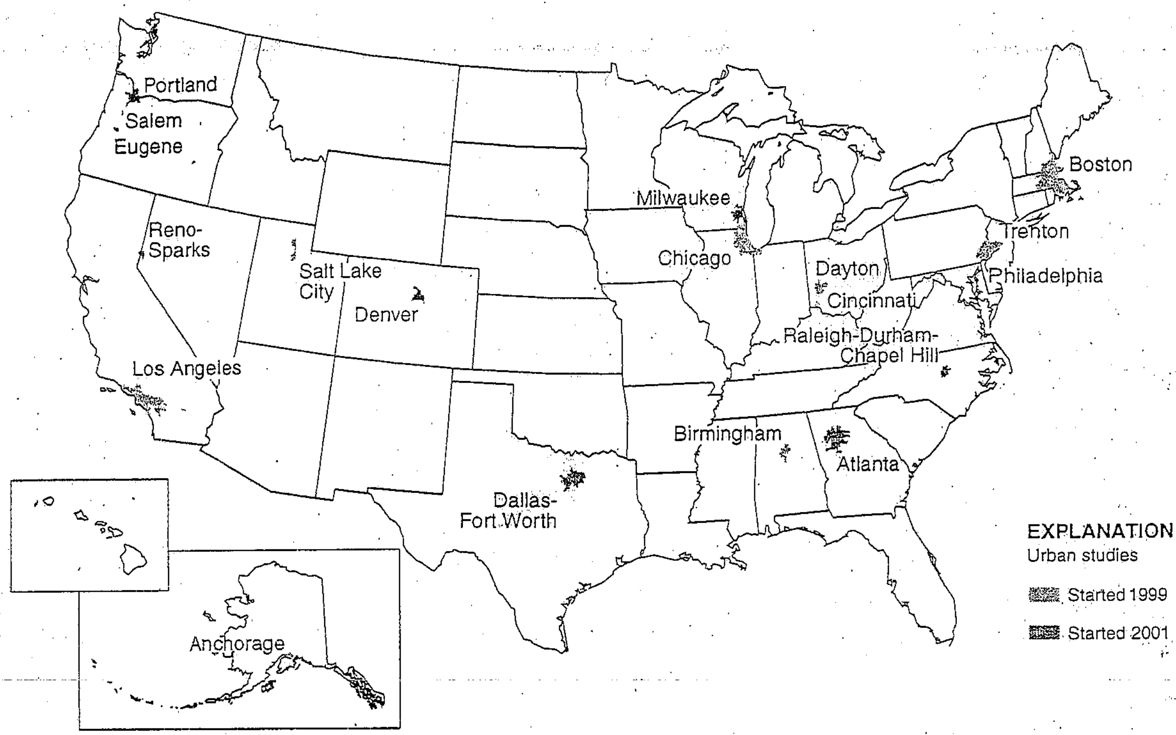
## How this information can be used

These studies will better define the interrelationships among water quality, stream hydrology and habitat, and ecosystems. In addition, the studies will lead to improved and comparable techniques for biological monitoring, and to the development of key indicators of the effects of urbanization on environmental quality. Information on the magnitude and pattern of degradation of stream ecosystems will help urban planners and other stakeholders prioritize streams for restoration. Understanding the effects of habitat disturbance, in addition to chemical contamination, within a given setting will help clarify the most appropriate strategy for managing, protecting, and restoring urban streams.

By Carol Couch and Pixie Hamilton

*See map and contact information on back*

## Locations of 15 metropolitan areas where NAWQA is studying the effects of urbanization on stream ecosystems

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**Internet access to supporting NAWQA technical and program information:**

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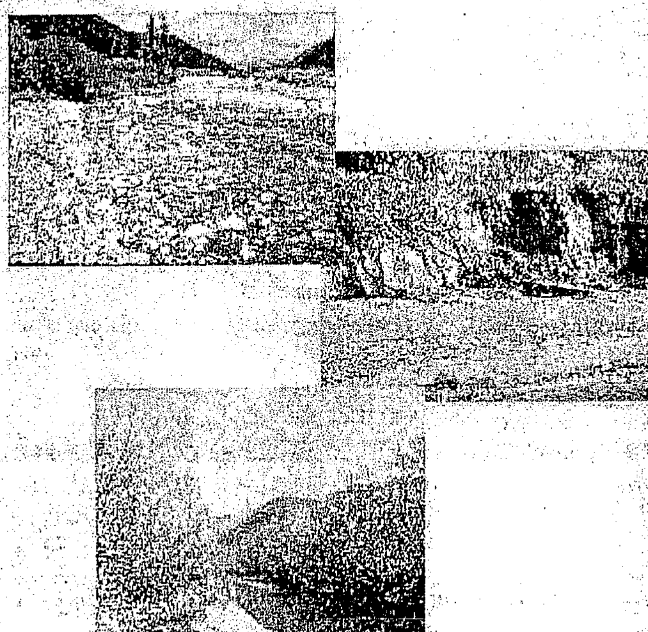
# Managing Runoff to Protect Natural Streams: The Latest Developments on Investigation and Management of Hydromodification in California



Eric D. Stein
Susan Zaleski

Southern California Coastal Water Research Project

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# Managing Runoff to Protect Natural Streams: The Latest Developments on Investigation and Management of Hydromodification in California

Proceedings of a Special Technical Workshop
Co-sponsored by:

- ***California Stormwater Quality Association (CASQA)***
- ***Stormwater Monitoring Coalition (SMC)***
- ***University of Southern California Sea Grant (USC Sea Grant)***

Eric D. Stein
***Southern California Coastal Water Research Project (SCCWRP)***

Susan Zaleski
***University of Southern California Sea Grant (USC Sea Grant)***

**December 30, 2005**

Technical Report #475

SMC

CASQA
CALIFORNIA STORMWATER QUALITY ASSOCIATION

Southern California Coastal Water Research Project
Established 1969

Sea Grant
University of Southern California

# EXECUTIVE SUMMARY

Stream channel downcutting, widening, and erosion due to increased surface runoff present the most profound and difficult to manage problems resulting from conversion of natural land surfaces to developed areas. Land use changes that reduce the capacity for infiltration and evapotranspiration of rainfall may result in an increase in the magnitude and frequency of erosive flows and changes in the proportion and timing of sediment delivery downstream. These effects, termed *hydromodification*, can adversely impact the physical structure, biologic condition, and water quality of streams.

This document summarizes the presentations and discussions from a workshop convened to provide an overview of key technical and managerial issues associated with hydromodification, with specific focus on California's climatic setting. The goal of this workshop was to identify key conclusions regarding the mechanisms and causes of hydromodfication and to provide managers and decision makers with a list of recommended priorities for future work in terms of both technical and managerial products.

Recent studies indicate that California's intermittent and ephemeral streams are more susceptible to the effects of hydromodification than streams from other parts of the United States (US). Physical degradation of stream channels in the central and eastern US can initially be detected when watershed impervious cover approaches 10%, although biological effects (which may be more difficult to detect) may occur at lower levels. In contrast, initial response of streams in the semi-arid portions of California appears to occur between 3% and 5% impervious cover.

Managing the effects of hydromodification requires attention to changes in runoff volume, magnitude of flows, frequency of erosive events, duration of flows, timing of high flows, magnitude and duration of base flows, and patterns of flow variability. Slope, composition of bed and bank materials, underlying geology, watershed position, and connections between streams and adjacent floodplains are also key considerations in the management of hydromodification effects.

A contemporary toolbox for assessing the effects of hydromodification consists of three technical approaches: continuous simulation modeling, physical process modeling using geomorphic metrics, and risk-based modeling. Independently and in a range of combinations, these approaches are instrumental to understanding and predicting channel responses. In conjunction with these approaches, the following research areas are recommended for enhanced understanding and assessment of hydromodification:

- Establishment of appropriate reference conditions for various stream types
- Establishment of linkage between geomorphic changes and biologic effects
- Development and calibration of linked models that provide long-term simulation of hydrologic, and resultant physical changes in channel morphology

Furthermore, ongoing monitoring programs should be established for reference streams, streams subject to effects of hydromodification, and streams where various hydromodification management strategies have been employed.

Hydromodification is best addressed with a suite of strategies including site design, on-site controls, regional controls, in-stream controls, and restoration of degraded stream systems. To improve the effectiveness of hydromodification management, it is important to identify the most appropriate set of strategies based on the type of channel, setting, stage of channel adjustment, and amount of existing and expected impervious cover in drainage catchments. Management of hydromodification could be improved by integrating it into a multi-objective strategy that addresses hydrology, water quality, flood control, and stream ecology. In addition, streams should be surveyed and classified in order to identify areas with the greatest risk of impact from hydromodification. Output from dynamic modeling can be used to develop easy to use management guides, and standard monitoring protocols and performance criteria need to be developed. These management tools should be geared toward application by land-use planners and regulators at the municipal and state levels. Finally, a hydromodification workgroup should be formed to facilitate communication and exchange of ideas and information on technical and management strategies relevant to hydromodification.

# ACKNOWLEDGEMENTS

This document summarizes two days of collaborative, prescient, and enlightening discussion on one of the most daunting challenges facing aquatic resource managers. We would like to thank all workshop presenters and panelist for sharing their insight and expertise to help develop the conclusions and recommendations contained in this document. We would like to especially thank the workshop organizing committee who made this event possible. Finally, we thank the California Association of Stormwater Quality Agencies, the southern California Stormwater Monitoring Coalition, and University of Southern California (USC) Sea Grant for their generous funding and support.

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# WORKSHOP OVERVIEW

The process of urbanization has the potential to affect stream courses by altering watershed hydrology. Development and redevelopment can increase impervious surfaces on formerly undeveloped (or less developed) landscapes and reduce the capacity of remaining pervious surfaces to capture and infiltrate rainfall. In addition, in semi-arid regions, development is usually accompanied by significant supplemental landscape irrigation that maintains high soil moisture conditions. Development practices also tend to reduce or eliminate native vegetation, thus reducing evapotranspiration of rainfall. Consequently, as watersheds develop, a larger percentage of rainfall becomes runoff during any given storm; runoff reaches stream channels much more rapidly, resulting in peak discharge rates that are higher than those for an equivalent rainfall prior to development. These changes to the runoff hydrograph have been termed *hydromodification*.

Hydromodification can result in adverse effects to stream habitat and water supply, and stream erosion associated with hydromodification often threatens infrastructure, homes, and businesses. In response to these effects, state and local agencies have developed, or are developing, standards and management approaches to control and/or mitigate the effects of hydromodification on natural and semi-natural stream courses.

On October 2 and 3, 2005, 26 speakers and 175 participants gathered in Ontario, California to discuss the results of recent research inside and outside of California. This technical workshop was convened to provide an overview of the key technical and managerial issues associated with hydromodification, with specific focus on California's climatic setting. The specific objectives of the workshop were:

- Exchange of information on technical and managerial approaches to hydromodification
- Identification of common conclusions regarding a general understanding of hydromodification
- Recommendation of priority needs for future work relevant to technical and managerial products in response to hydromodification issues

The workshop consisted of two evening and one all-day session. The first night, a small group of scientists and managers gathered to discuss key knowledge gaps and technical information needs. The day session was open to all attendees, who interacted with a slate of speakers summarizing technical, regulatory, and management approaches to responding to the effects of hydromodification. The workshop concluded with an evening session in which a small group discussed priority needs for future research and management tool development. The agenda for the workshop is provided in Appendix A.

This document summarizes key conclusions resulting from the presentations and discussions that occurred during the workshop. The document also provides managers and decision makers with a list of recommend priorities for future work in terms of both technical and managerial products related to hydromodification response.

## INTRODUCTION TO HYDROMODIFICATION

Hydromodification is defined by the Environmental Protection Agency (EPA) as the "alteration of flow characteristics through a landscape which has the capacity to result in degradation of water resources" (http://www.epa.gov/owm/mtb/cwns/1996rtc/glossary.htm). Most often, hydromodification results from changes in land use practices or direct management of surface runoff. Consequences of hydromodification can include stream channel incision, aggradation, desiccation, and/or inundation.

Land use practices over the past several hundred years have resulted in hydromodification of western landscapes (Haltiner et al. 1996, Leopold 1968). Historically, many small streams were not connected to main river channels, but rather existed as shallow swales and wetland systems connected to larger rivers via subsurface flow. Surface hydrologic connections occurred intermittently following periodic large storm events. Increased surface runoff and channel disturbance, beginning during the cattle-grazing era circa 1700 – 1900, resulted in many of these systems becoming permanently channelized (Cooke and Reeves 1976). Channel modification through either direct alteration, or as a consequence of changes in patterns of surface runoff, e.g. through increases in impervious cover, continues today.

Hydromodification has typically resulted in channel incision and bank erosion in the upper and middle portions of the watershed, and in deposition, aggradation, and increased channel meandering in the downstream, flatter portions of the watershed. Often, as the main channel has incised, the lowered base level results in the formation of "knickpoints" (abrupt drops in the channel floor) that migrate upstream into the headwater areas. Often, these migrating "knickpoints" result in severe gully formation in lower-order streams, i.e. first- through third-order streams, based on the Strahler stream ordering system. These smaller headwater streams are important from a watershed perspective because much of the sediment generation, carbon export, and initial nutrient processing occur in the upper watershed (Rheinhardt et al. 1999). The vast majority of stream miles in any given watershed exist as small headwater streams (Beschta and Platts 1986); consequently, impacts to these streams can result in profound cumulative effects to sediment and water movement patterns throughout the watershed. In many areas, the majority of remaining semi-intact streams is in the upper portions of watersheds. Notably, these areas are the most susceptible to land use change and associated effects of hydromodification. When development occurs in headwater areas rather than lower in the watershed, it tends to result in larger increases in peak discharge due to cumulative decreases in the time of concentration of rainfall to runoff (Beighley and Moglen, 2002).

Small, frequent runoff events, i.e. two-year frequency storms and smaller, demonstrate the most dramatic effects due to increased imperviousness, effects of supplemental irrigation, or other changes in land use practices (Beighley et al. 2003, Donigian and Love 2005, Hollis 1975). These small events account for the majority of long-term movement of sediment and consequently are the most deterministic of the geomorphic stability of the stream channels (Wolman and Miller 1960). However, small increases in basin impervious cover can also result in dramatic increases in runoff during 0.5-5 year flow events. For example, an increase of a few percent in impervious cover can increase the magnitude of a 1- or 2-year flood event by 20-fold (Hollis 1975, Urbonas and Roesner 1992).

Studies from parts of the country with climates more humid than California's indicate that physical degradation of stream channels can initially be detected when watershed impervious cover approaches 10%, although biological effects, which may be more difficult to detect, may occur at lower levels (CWP 2003). Recent studies from both northern and southern California indicate that intermittent and ephemeral streams in California are more susceptible to the effects of hydromodification than streams from other regions of the US, with stream degradation being recognized when catchment's impervious cover is as little as 3-5%[1] (Coleman et al. 2005). Furthermore, supplemental landscape irrigation in semi-arid regions, like California, can substantially increase the frequency of erosive flows (AQUA TERRA Consultants 2004). However, because all streams are constantly undergoing change and adjustment, effects of impervious cover should be investigated in terms of changes in the rate of channel response in addition to the absolute magnitude of response.

Managing the effects of hydromodification requires attention to more than just the peak runoff. The work (or energy) that affects physical and biological channel structure results from movement of water and sediment controlled by runoff volume, flow magnitude and duration, frequency of erosive events, timing of high flows, and magnitude and duration of base flows (Konrad and Booth 2005, Montgomery and MacDonald 2002, Paul and Meyer 2001, Roesner and Bledsoe 2003). Changes in patterns of flow variability and increases in the frequency of high flows have been shown to have measurable effects on the community composition of stream biota (Konrad and Booth 2005). Because streams are coupled hydrologic, geomorphic, biologic systems, it is important to understand the various effects of all changes in surface runoff patterns and to develop appropriate management strategies for each potential effect.

As channels incise, they often go through a series of adjustment stages from initial downcutting, to widening, to establishing new floodplains at lower elevations (Figure 1). This process can occur over years or decades depending on the type of channel and flow regime. Sand-dominated channels may pass through the full sequence of stages in a few decades, whereas channels in more resistant materials, such as clay, may take much longer, in some cases 50–100 years (Roesner and Bledsoe 2003). Therefore, it is important to understand a channel's stage of adjustment, and target management strategies to account for current and expected future evolution of the channel form.

[1] Most studies evaluate the response of stream channels to "total impervious cover". However, a more appropriate assessment would be based on "effective impervious cover", i.e., the amount of impervious cover that is hydrologically connected to the stream channel. Assessment based on effective impervious cover is more likely to result in observed channel response at lower levels of imperviousness.

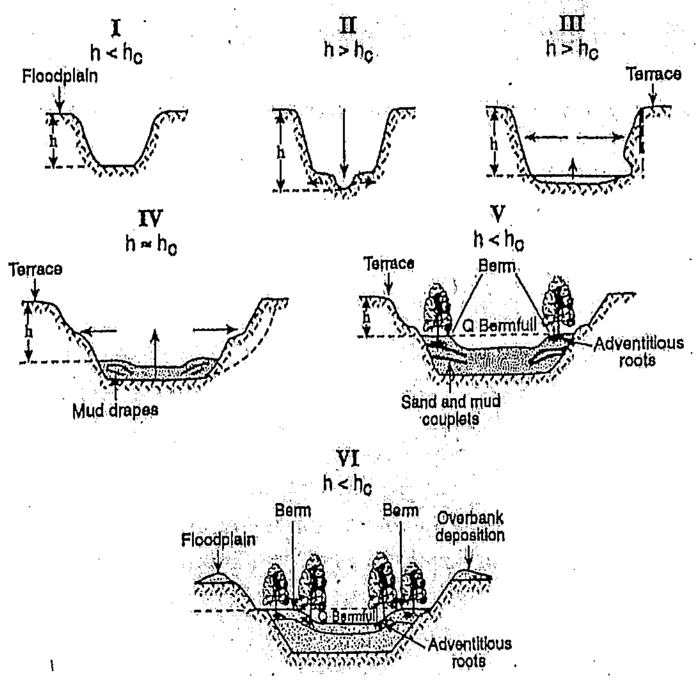


**Figure 1: Stages of sand-bed channel adjustment (Schumm et al. 1984).**

The pattern and rate of channel response to hydromodification will vary based on channel type and recent disturbance history (Montgomery and MacDonald 2002). Underlying geology, composition of bed and bank materials, slope, watershed position, and floodplain connectivity all affect channel response. Several stream classification systems have been developed over the years, including Shumm (1963), Montgomery and Buffington (1993), Rosgen (1994), and Church (2002). Most of these systems classify streams based on their sensitivity to change and therefore can be used to help assess, prioritize, and customize hydromodification management approaches. For example, Montgomery and Buffington (1993) define the following five channel types, listed from most to least resilient:

- Cascade
- Step pool
- Plane bed
- Pool riffle
- Dune ripple

Classification systems provide a useful starting point for evaluation of channel response to hydromodification; however, the classification systems above were developed in regions more humid and/or mountainous than those typical to California. Given differences in substrate and the extreme range of flows typically observed in arid regions, it is important to develop and regionally calibrate a classification system for dryland channels. Furthermore, the assessment of channel condition and the development of management strategies must be interpreted in terms of both spatial context (i.e. valley slope and position within the watershed) and temporal context (i.e. disturbance history) of the stream (Montgomery and MacDonald 2002). For example, channel incision may be most dramatic in the middle portions of the watershed; however, these reaches may have stabilized, while the most active erosion and sediment production is occurring in smaller headwater channels. For these reasons, simplistic classification and assessment schemes based on channel appearance must be supported by in-depth geomorphic assessment, historical studies, and thorough understanding of physical and hydrologic processes.

Ultimately, some management strategies may vary based on the channel type, as well as the degree of current and anticipated hydromodification, while others may be more uniformly applied. For example, controlling the magnitude and duration of runoff may be an effective strategy for all stream types, while bioengineered streambank stabilization may only be effective for specific stream types under specific circumstances.

# TECHNICAL APPROACHES TO ASSESSING HYDROMODIFICATION

The contemporary toolbox for assessing the effects of hydromodification consists of several technical approaches that may be combined in various ways. Continuous simulation hydrologic models can be used to assess elements in rainfall-runoff cycles and to describe conditions of flow in stream channels. These approaches can be used to assess the way changes in land cover may affect stream flow and to develop management strategies aimed at preventing or reducing such effects. A second, more involved approach, physical process modeling uses hydrologic models to predict changes in stream flow and to predict how these changes may affect the physical structure of the channel itself. This approach may couple hydraulic and sediment transport models, and/or incorporate geomorphic metrics to predict whether or not a channel will remain stable when subjected to the effects of hydromodification. Finally, risk-based assessments are used to account for the uncertainty associated with long-term cumulative effects of altered hydrology on stream channel flow, sediment transport, and stream geomorphology.

## Continuous Simulation Modeling

Continuous simulation modeling provides a powerful tool for investigating the way rainfall-runoff patterns change over time with respect to normal climatic cycles and changes in land use practices. Hydrologic models integrate land use, precipitation, soils, topography, and other physical factors to simulate resultant runoff patterns. These models can be used to evaluate the way changes in the extent and distribution of impervious cover may affect flow magnitude, timing, frequency, and duration. In addition, continuous simulation models can be used to assess changes in the shear stress of channel beds and banks over time. Predicted shear stress ($\tau_{actual}$) values can be compared to critical shear stress ($\tau_{critical}$) values associated with the onset of erosion in order to predict conditions that may result in initiation of scour. Recent studies in Ventura County have successfully used $\tau_{actual}/\tau_{critical}$ values between 1.2 - 1.5 as a threshold for initiation of channel scour along with an assessment of the frequency of occurrence of these erosive flow events (AQUA TERRA Consultants 2004). When using hydrologic models it is important to simulate runoff and erosion patterns over periods of at least 20-30 years. Short-term or single-event modeling is not sufficient to capture the continuous erosion and aggradation processes that occur during large and small storm events over extended periods of time.

## Physical Process Modeling/Geomorphic Metrics

Physical process modeling aims to establish relationships between impervious cover, runoff patterns, and channel response based on field observations of changes in channel form over time. These field observations are used to derive mathematical relationships that can be used to predict channel response to changes in land use practices. Erosion Potential ($E_p$) is a geomorphic metric that has been used in several recent studies relevant to the effects of increased runoff associated with increases in impervious cover. The $E_p$ represents the ratio of pre- and post-development erosive forces for a given stream type, expressed as:

$$E_p = \frac{W_{post}}{W_{pre}}$$

Where: $W_{post}$ = Cumulative erosive energy or work after development
$W_{pre}$ = Cumulative erosive energy or work before development

Where: Erosive energy is defined as the energy that is above the threshold of erosion for the stream boundary materials, also referred to as excess specific stream power

Values for $E_p$ are derived for both the channel bed and bank, and the boundary that is more susceptible to erosion is used as the basis of setting response thresholds. The $E_p$ of a stream channel should be evaluated based on long-term simulations (e.g. 50 yrs) or based on empirical data collected over extended periods of time. Geomorphic metrics can be used to project changes in channel cross-section area over time in response to increases in impervious cover, as shown in Figure 2, which describes the expected effect of increases in total impervious cover (TIMP) on channel cross-sectional area. Channel response thresholds can be inferred according to inflection points on the curve. In this plot, the upper curve is derived from southern California data; the lower curve is derived from data observed in other parts of the US. Expected threshold of response for southern California streams is approximately 4% (Coleman et al. 2005).

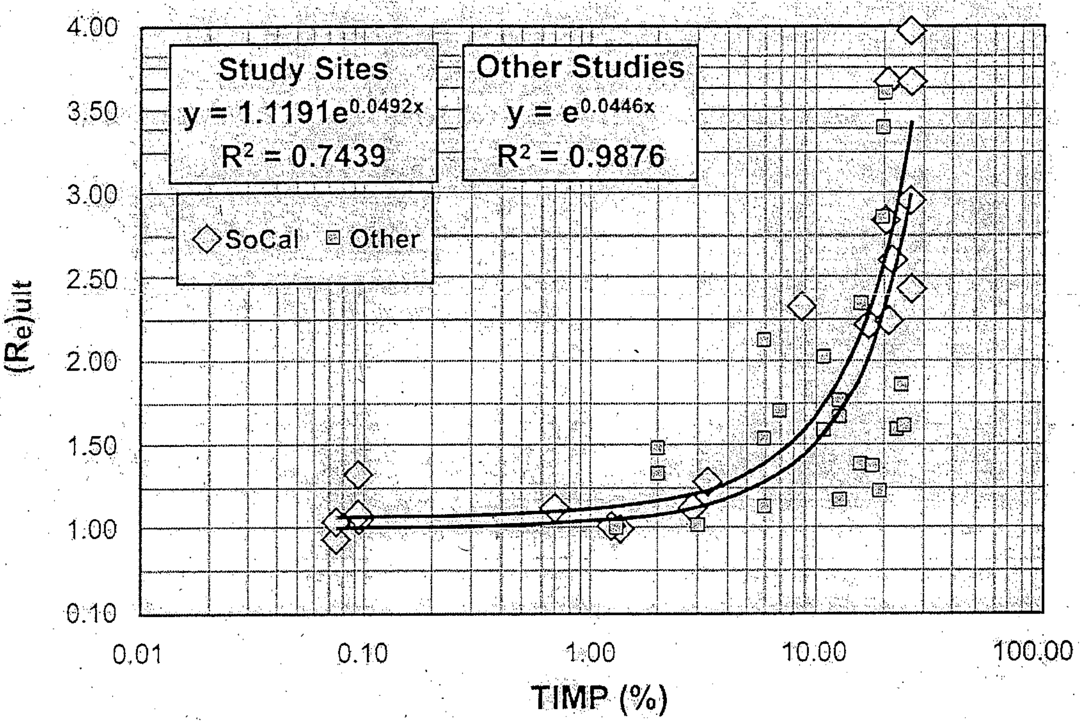


**Figure 2: Enlargement curve showing expected effect of increases in total impervious cover (TIMP) on channel cross-sectional area. (Re) is the ratio of ultimate channel cross-sectional area to current cross sectional area. Upper curve is derived from data from southern California, lower curve is derived from data from other parts of the US. Expected threshold of response for southern California streams is approximately 4% (from Coleman et al. 2005 and C. MacRae).**

It is important to note that curves such as those shown in Figure 2 assume a consistent hydrologic response to increased impervious cover. Long-term hydrologic simulations should be coupled with physical process models to fully explore these relationships and help validate the curves. Furthermore, different channel types respond differently to changes in runoff. Therefore, an enlargement curve, such as the one shown in Figure 2 for a single channel type, should be developed for each major channel type in a region in order to help focus the timing and location of strategic runoff management measures.

## Risk-based Modeling

Unlike physical process modeling, which aims to establish response thresholds, risk-based modeling estimates the probability of channel response to increases in erosion potential associated with anticipated changes in runoff as a result of increases in impervious cover. Managers can then determine acceptable risk levels. Typically, risk-based modeling uses the output of continuous simulation or physical process models to generate time-series data relevant to flow and sediment transport. Often this type of modeling includes linear and logistic regressions, in addition to probability networks. These data are then used to estimate the risk of channel response with respect to anticipated changes in runoff volume and sediment. Figure 3 provides an example of the way logistic regression analysis can be used to estimate the likelihood of channel instability based on progressive degrees of erosion potential.

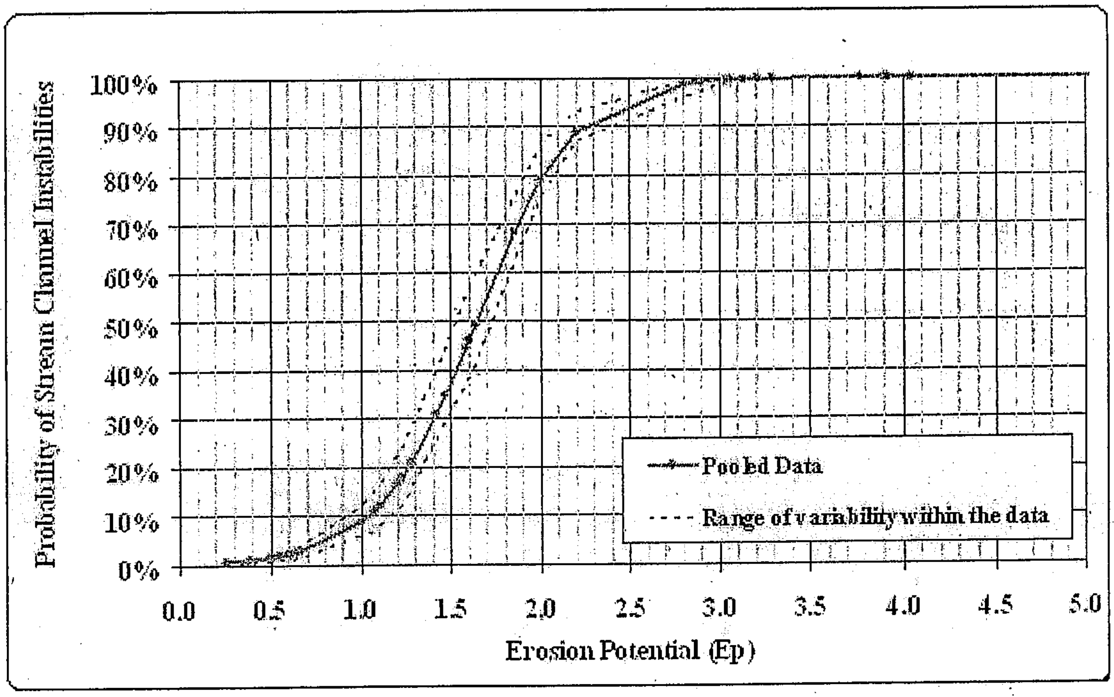


**Figure 3: Logistic regression analysis showing the probability of various channel erosion potentials (from B. Bledsoe).**

For studies conducted in the San Francisco Bay Area, an $E_p$ value of 1.2 was proposed as an acceptable threshold based on a 15% probability of channel instability[2]. This was typically associated with approximately 3 - 6% impervious cover for channels in sand substrates and 10-12% for channels in clay substrates.

[2] The negotiated Ep value of 1.0 was adopted for the final Hydromodification Management Plan for Santa Clara Valley and included in a permit amendment for agencies in that area.

## PRIORITY TECHNICAL NEEDS AND INFORMATION GAPS

Workshop participants identified five priority areas for additional research and data collection:

- Regional reference conditions for various stream channel types
- Links between geomorphic change and biologic effects
- Dynamic simulation models calibrated for local conditions
- Potential consequences of increased storm water infiltration from urbanized areas
- Ongoing monitoring programs to assess hydromodification impacts and to develop effective management strategies

### *Regional reference conditions for various stream channel types need to be established*

Because most areas in the western US have been subjected to historic grazing or logging, many channels in this region have undergone some degree of change over time. Furthermore, the dynamic nature of this region's fluvial systems means that these streams are constantly undergoing some degree of change. Understanding the historic conditions of stream channels can provide valuable insight; however, historic conditions may not be the most appropriate "reference" in light of current constraints. Rather, reference should be considered a condition where stream channels are in a state of dynamic equilibrium under contemporary natural watershed processes. Once a regional reference condition is defined, data on flow, sediment movement, and geomorphology should be collected on an ongoing basis from representative reference stream reaches. These data will facilitate modeling that more effectively differentiates natural cycles from human-induced changes, especially during long wet or dry cycles where changes may be dramatic but infrequent.

### *Links between geomorphic change and biologic effects need to be more clearly defined*

Hydromodification can cause a variety of physical changes to streams. However, hydrologic changes that are most relevant to biologic communities have not been well defined. For example, it is unclear how changes in base flow duration; peak flow magnitude, duration, and timing; or flow variability affect the structure and function of stream communities. Ultimately, there is a need to develop biologic indices to assess the effects of hydromodification and more effectively direct management strategies.

### *Dynamic simulation models need to be developed and calibrated for local conditions*

Although continuous hydrologic simulation and physical process models have been developed for California streams, these models have not been routinely linked to the assessment of stream channel response to various forms of hydromodification. Hydrologic, physical process, and risk-based models are much more effective when used in combination and appropriately calibrated and validated for California streams. The resultant tool(s) can greatly improve assessments that predict the likelihood of stream channel response to anticipated changes in hydrology associated with changes in land use patterns. Model output may also be useful in the development of objective criteria for establishing land use practices that minimize hydromodification effects, designing tools for best management practices (BMP) design, and evaluating the performance of management measures.

*Potential consequences of increased storm water infiltration from urbanized areas need to be investigated*

Infiltration of substantial volumes of storm water runoff from developed land surfaces may introduce unacceptable levels of contaminants into groundwater and/or shallow aquifers. The risk of groundwater contamination and the fate of pollutants introduced into subsurface waters need to be investigated by increased monitoring, development of coupled surface water-groundwater models, and implementation of demonstration projects.

*Ongoing monitoring programs to assess hydromodification impacts and develop effective management strategies need to be designed and implemented*

First, more extensive flow monitoring needs to be instituted to compensate for the difficulty of calibrating hydrologic models for un-gauged headwater streams. Second, regular geomorphic data needs to be collected from reference streams as well as streams subject to the effects of hydromodification. Routine measurement of channel cross-sections and substrate will greatly improve understanding of channel adjustment processes and allow better discrimination between natural and anthropogenic changes. Third, streams subject to various hydromodification management strategies need to be monitored and documented to support adaptive management and education on emerging techniques and strategies.

# REGULATORY AND MANAGEMENT STRATEGIES

## Regulatory Approaches to Address Potential Effects of Hydromodification

A variety of regulatory programs and tools exist to help in the regulation of hydromodification effects, including:

- Clean Water Act Section 401 certifications
- Total Maximum Daily Loads (TMDLs)
- Municipal storm water (MS4) permits under Section 402 of the Clean Water Act, and the associated Standard Urban Storm Water Mitigation Program (SUSMP) requirements
- Watershed Urban Runoff Management Plans (WURMPs) and the Watershed Management Initiative (WMI) which encourage municipalities to work cooperatively to manage issues such as hydromodification

In addition, California Environmental Quality Act/National Environmental Policy Act (CEQA/NEPA) processes can be used to better address hydromodification issues, especially with regard to cumulative effects.

Looking to the future, Regional Water Boards in California are considering development of numeric criteria and objectives for new development and redevelopment projects to offset and/or mitigate hydromodification effects. These objectives may involve requirements for managing flow and/or reducing effective impervious cover as well as strategies to maximize infiltration and reuse of storm water. Some Regional Boards are also considering ways to better coordinate with other regulatory agencies that have authority over hydromodification and stream alteration. Similarly, some State and Regional Water Boards are evaluating their existing regulatory authority over hydromodification and considering ways to strengthen their authority, particularly under section 401 of the Clean Water Act, or as part of Basin Plans.

## Management Approaches to Address the Effects of Hydromodification

Hydromodification is best addressed by using a suite of strategies, including site-design, restoration of degraded stream systems, as well as in-stream, on-site control, and regional controls. Managers need to identify the most appropriate set of strategies based on channel type and setting, channel adjustment stage, and amount of existing and anticipated impervious cover in the drainage catchment. However, attempting to have the post-development condition match pre-development runoff magnitude and duration should be an initial consideration for all circumstances.

Management strategies should address not only changes in peak flows but also changes in flow duration and sediment yield. Research to support development of several recent Hydromodification Management Plans indicates that post-project BMPs should ensure no change in runoff volume and cumulative duration of all flows greater than the critical flow for bed or bank mobility. Case studies of three Hydromodification Management Plans/Strategies are provided in Appendix B.

Over the long term, land-use planning, runoff management, as well as channel and floodplain restoration, should be the cornerstones of any hydromodification management strategy. The planning cycle for new development or re-development projects should begin with hydromodification management assessment as part of the preparation of General and Specific Plans, master drainage plans, and zoning designations. Hydromodification effects must be managed with respect to long-term cycles; therefore, strategies should be adaptive. As conditions change and stream channels evolve, the management approaches must be adjusted. However, it is important to recognize that because changes to watershed hydrology are continual; it is unlikely that any management strategy will be able to achieve full hydrologic mitigation. Over the long term, some lasting physical and biological effects should be expected. Management goals should realistically reflect these anticipated changes.

The Center for Watershed Protection, the National Association of Homebuilders, the Water Environment Research Foundation, the Bay Area Stormwater Management Agencies Association, and others have developed resources that land managers can use to guide improved site design. A list of some of these resources is provided in Appendix C.

## PRIORITY MANAGEMENT NEEDS

In response to rapidly developing technical tools, regulations, and management goals, workshop participants identified the following management and information priorities:

1. Establish mapping and classification of streams based on their susceptibility to hydromodification effects. Susceptibility should be evaluated with respect to both stream properties, potential for future increases in impervious cover, and concomitant changes in land use practices, such as supplemental irrigation. Such a system would help managers prioritize streams requiring protection and hydromodification management.

2. Model stream systems in ways that are useful for regulators to make decisions. Once models are validated with local data, output should be:
   - Readily understandable and usable by planners and managers
   - Easily interpreted by regulators for development of consistent requirements and evaluation criteria for the specific region
   - Readily used to develop standardized flow control sizing and design tools for BMPs, where applicable

3. Develop a series of management tools that can be easily used to make recommendations or set requirements relative to hydromodification for new development and re-development projects. These tools would utilize the results of monitoring, modeling, and assessment completed under previous projects to develop a series of plots, nomographs, checklists, or similar managerial tools. It is envisioned that ideally, tools should be developed for three different levels of analysis:

   <u>Screening tools</u> – Checklists or similar tools that allow planners and managers to evaluate whether or not a project is likely to involve substantial hydromodification issues.

   <u>Effects tools</u> – For projects that are considered likely to have hydromodification effects based on the results of the screening tool, this tool would serve as a nomograph or series of plots used to evaluate the expected magnitude or intensity of effects associated with a particular project. This tool could also be used to identify projects that should be subjected to subsequent in-depth analysis.

   <u>Mitigation tools</u> – Once the expected magnitude of effects are determined, this tool would be used to guide recommended mitigation and management measures. This tool could be a series of fact sheets, design criteria, and sizing standards to be used to aid in the development of standards or mitigation requirements.

4. Construct metrics and monitoring protocols to measure the effects of hydromodification on biological communities including riparian habitat.

5. ~~Determine standard monitoring protocols for hydromodification~~ effects and facilitate regional information sharing on project performance.

6. Evaluate the relative costs and benefits of hydromodification management at the site level (e.g. low impact development), and at the regional level (e.g. large retention and infiltration facilities). The economic costs of hydromodification have not been well documented, nor have the economic benefits of managing the physical and biological

effects of hydromodification. Information is also needed on the cost to maintain and manage hydromodification BMPs.

7. Establish recommended short-term measures for use while longer-term solutions, such as low-impact development and alternative site design are evolving.

In addition to management and information priorities, several institutional barriers were identified that may hinder effective management of hydromodification effects. Steps to overcome such barriers include:

A. Hydromodification management needs to be part of an integrated multi-objective management strategy. Stream planning and management should integrate hydromodification, water quality, flood control, and habitat management strategies as a whole rather than addressing each issue in isolation. Increased coordination between agencies, departments, and stakeholders should be strongly supported. Specifically, agencies that have authority over hydromodification and stream alteration should work toward coordinating regulatory approaches to achieve greater consistency.

B. Local ordinances need to be revised to facilitate integrating water quality and water quantity management into project design. These ordinances should be flexible enough to allow for variances from standard design requirements, such as curb and gutter and street width parameters, to help reduce impervious cover and increase infiltration.

C. Hydromodification needs to be addressed in both General and Specific Plans in terms of the location and design of new development. Site-by-site or project-specific approaches tend to be less effective and more costly to implement.

D. Better linkage between theory and practice need to be established through case studies, academic research, demonstration projects, and long-term BMPs monitoring.

E. Management of hydromodification needs to be incorporated into regional resource planning efforts, such as the Corps of Engineers Special Area Management Plans (SAMPs) or US Fish and Wildlife Service's Multi-species Habitat Conservation Plans. These regional planning efforts may be effective tools to address cumulative effects of hydromodification at the watershed scale.

F. A more effective public communication and education strategy needs to be developed. Property owners, local businesses, and community groups need to be better educated about the causes and effects of hydromodification in the context of the watersheds where they live and work. Simple definitions of streams and watersheds should be provided as part of the education strategy. Hydromodification effects need to be linked to health, aesthetic, recreational, and economic endpoints. Citizens should be made aware of simple actions, such as redirecting downspouts, using xeriscaping, and installing planter boxes, that help reduce hydromodification effects.

G. An ongoing working group should be established to coordinate research, monitoring, technology transfer, education, and management approach evaluation that includes all stakeholder groups.

# CONCLUSIONS AND RECOMMENDATIONS

Presentations and discussions during the two-day hydromodification workshop resulted in the following key conclusions and recommendations:

## Conclusions

- Physical degradation of stream channels in semi-arid climates of California may be detectable when basin impervious cover is between 3% and 5%. However, biological effects are probably occurring at lower levels.
- Frequent, 0.5-5 years, small runoff events, are most affected by hydromodification.
- Not all streams will respond in the same manner. Certain management strategies need to account for differences in stream type, stage of channel adjustment, current and expected amount of basin impervious cover, and existing or planned BMPs.
- Management strategies should address effects on flow magnitude, duration, and volume.
- Assessment of potential effects and suitability of possible management approaches must account for decadal scale climatic cycles and associated stream channel response.
- Improved site design is likely to be the most effective hydromodification management strategy and should be incorporated at the planning stage of a project.
- It is unlikely that all the effects of hydromodification can be fully mitigated. Changes in impervious cover will result in some changes to the flow patterns and ecology of the affected stream. Realistic management goals should be established to acknowledge long-term effects of increased impervious cover.

## Recommendations

- Integrate management of hydromodification into a multi-objective strategy that addresses hydrology, water quality, flood control, stream ecology, and overall watershed and land use planning.
- Institute interim management measures until runoff management becomes a more standard and accepted element of site design, for example, low impact development principles become commonly accepted and implemented in all site designs.
- Establish and implement a stream channel classification system based on expected vulnerability of different streams to hydromodification-induced change.
- Establish appropriate regional reference conditions should for each stream type based on the established classification system.
- Develop and calibrate dynamic simulation models for local streams. Models that combine continuous hydrologic simulations, physical process models, and risk-based modeling will be the most effective.
- Establish ongoing regional hydromodification monitoring programs. These programs should collect flow and geomorphic data from reference streams, unmitigated streams impacted by hydromodification, and streams subject to hydromodification management measures. Helping to separate natural variability from urban-induced changes in stream condition should be a primary goal of such ongoing monitoring programs.
- Develop indices to assess the biological effects of hydromodification.

- Develop protocols for measuring the economic costs and benefits of hydromodification management. Assemble case studies that document these economic costs and benefits.
- Initiate a hydromodification workgroup to facilitate exchange of ideas and information on technical and managerial approaches.
- Increase public education about what can be done at homes, businesses, and in the community to address hydromodification effects.

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# APPENDIX A – WORKSHOP AGENDA

## HYDROMODIFICATION WORKSHOP AGENDA – October 2-3, 2005

### Sunday Evening, Invited Session

5:00- 5:15 **Welcome and Introductions** – Eric Stein (Chair), *Southern California Coastal Water Research Project*

5:15 – 5:30 **Regulatory Perspective** – John Robertus, *San Diego Regional Water Quality Control Board*

5:30 – 6:30 ***Status of Science on Evaluating/Studying Hydromodification*** (panel discussion)

- Jeff Haltiner, *Philip Williams and Associates*
- Gary Palhegyi, *Geosytec Consultants*
- Craig MacCrae, *Aquafor Beech*
- Brian Bledsoe, *Colorado State University*
- Derek Booth, *University of Washington*

7:30 – 8:30 **Dinner and Open Discussion of Data Gaps and Areas for Future Research**

### Monday, Open Session

8:30 – 8:40 **Welcome and Opening Remarks** – Chris Crompton (Chair), *SMC*

8:40 – 9:15 **Introduction to Hydromodification** – Jeff Haltiner, *Philip Williams and Associates*

9:15 – 10:15 ***Why is Hydromodification Such a Big Deal?*** (mini-panel discussion)

- Policy Perspective – Susan Cloke, *Los Angeles Regional Water Quality Control Board*
- Regulatory Perspective – John Robertus, *San Diego Regional Water Quality Control Board*
- Homebuilders Perspective – Marolyn Parson, *National Association of Home Builders*
- Natural Resource Perspective – Shelley Luce, *Santa Monica Bay Restoration Commission*

10:15 – 10:30 **Break ~**

10:30 – 12:30 **Hydromodification Research and Studies**

- Risk-Based Channel Stability Analysis for Urbanizing Watersheds – Brian Bledsoe, *Colorado State University*
- Changes in Streamflow Patterns from Urbanization: A Humid-Region Perspective – Derek Booth, *University of Washington*
- Modeling Urbanization Impacts and Channel Stability in Ventura County – Tony Donigian, *AQUA TERRA Consultants*
- Southern California Peak Flow study results and conclusions – Craig MacRae, *Aquafor Beech*
- Santa Clara Valley HMP Studies- Gary Palhegyi, *GeoSyntec Consultants*

12:30 – 1:30 **Lunch ~**

1:30 – 2:15 **Regulatory Response to Hydromodification**

- Northern California Perspectives – Larry Kolb, *San Francisco Bay Regional Water Quality Control Board*
- Southern California Perspectives – Xavier Swamikannu, *Los Angeles Regional Water Quality Control Board*

2:15 – 3:30 **Implementation of Hydromodification Management Practices**

- Contra Costa County – Dan Cloak, *Dan Cloak Consulting (for Contra Costa County)*
- Santa Clara Valley – Jill Bicknell, *Santa Clara Valley Urban Runoff Program*
- Newhall Land and Farming– Mark Subbotin, *Newhall Land and Farming Company*
- Control of Hydromodification Through Land Planning – Laura Coley-Eisenberg, *Rancho Mission Viejo*

3:30 – 4:30 **Panel Discussion on Implementation Issues** – Facilitated by Matt Yeager, *San Bernardino County Flood Control District*

- Rene DeShazo, *Los Angeles Regional Water Quality Control Board*
- Mark Abramson, *Heal the Bay*
- Marolyn Parson, *National Association of Home Builders*
- Jeff Haltiner, *Philip Williams and Associates*
- Jill Bicknell, *Santa Clara Valley Urban Runoff Program*

MONDAY EVENING, INVITED SESSION

5:30 – 6:00 **Welcome & Summary of Open Session** – Matt Yeager, *San Bernardino County Flood Control District*

6:00 – 7:00 **Dinner ~**

7:00 – 8:00 **Key Needs of Managers for Addressing Hydromodification** (panel discussion)

- Jeff Pratt, *Ventura County Watershed Protection District*
- Bill DePoto, *Los Angeles County Dept. of Public Works*
- Aaron Allen, *US Army Corps of Engineers - Regulatory Branch*
- Laura Coley-Eisenberg, *Rancho Mission Viejo*
- Jon Bishop, *Los Angeles Regional Water Quality Control Board*
- Rebecca Drayse, *TreePeople*

8:00 – 8:30 **General Conclusions and Outline for Workshop Report**

# APPENDIX B – CASE STUDIES

## Case Study 1 – Contra Costa County

Contra Costa County's Hydromodification Management Plan was developed in response to the National Pollutant Discharge Elimination System (NPDES) permit requirements from the San Francisco Bay Regional Water Quality Control Board. The goal of this Hydro-modification Management Plan (HMP) is to protect urban watersheds from ongoing hydro-modification by applying these requirements to development projects that are greater than or equal to 1 acre. They assist applicants to comply by providing designs and sizing factors. Permit conditions require municipalities to propose a plan to manage increases in flow and volume where increases could:

- Increase erosion
- Generate silt pollution
- Impact beneficial uses

The goal of these plans is to ensure that post-project runoff does not exceed pre-project rates and durations. Contra Costa's plan encourages Low Impact Development Integrated Management Practices (LID IMPs) and allows proposals for stream restoration in lieu of flow control where benefits clearly outweigh potential impacts. The plan includes four options for compliance:

1. Demonstrate project will not increase directly connected impervious area
2. Implement pre-designed hydrograph modification IMPs
3. Use a continuous simulation model to compare post- to pre-project flows
4. Demonstrate increased flows will not accelerate stream erosion

Management approaches are selected according to risk:

- Low risk = channelized systems
- Medium risk = channels in substrates with high bed and bank resistance
- High risk = all other channels

Project proponents need to develop a comprehensive analysis of management options for all high risk channels.

## Case Study 2 – Santa Clara Valley

The Santa Clara Valley Urban Runoff Pollution Prevention Program's (SCVURPPP's) NPDES permit requires that increases in runoff peak flow, volume, and duration shall be managed for all projects involving one or more acres of impervious cover, where increased flow and/or volume can cause increased erosion of creek beds and banks. SCVURPPP's overall approach to creating a HMP was to conduct geomorphic and hydrologic assessments of three representative watersheds in the valley, conduct channel stability analyses to establish thresholds for hydromodification control, develop design criteria for flow control measures, and provide guidance for best management practice implementation[3].

The performance criteria in the HMP state that post-project runoff shall not exceed estimated pre-project rates and/or durations, where the increased storm water discharge rates and/or durations will result in increased potential for erosion. Projects shall not cause an increase in Ep of the receiving stream over the pre-project (existing) condition. Furthermore, the Ep value should not be increased at any point downstream of the project. These requirements can be met with a combination of on-site and off-site control measures.

On-site controls should be designed to match flow-duration curves of post-development conditions to pre-development conditions for all flows between 10% of the 2-year peak flow and the 10-year peak flow. Example sizing of flow-duration basins are shown in Table B-1. Management measures are considered "practicable" if construction cost of treatment plus flow controls is less than or equal to 2% of project cost, excluding land value.

**Table B-1: Basin Sizing Case Studies from the Santa Clara Valley Urban Runoff Program Hydromodification Management Plan (SCVURPPP Final HMP Report, 2005).**

| | Thompson | San Jose | Alameda |
|---|---|---|---|
| **Basin Depth** | 4 feet | 2.25 feet | 2 feet |
| **Basin Area** | 30 acres | 0.06 acre | 0.8 acre |
| **Basin Size % DCIA** | 5.7% (4% catchment) | 3.7% (1.7% catchment) | 10% (7% catchment) |
| **Drain Time** | 3 days (90% of the time) | < 1 day | 1 day |
| **$Q_{cp}$ (low flow)** | 2.4 cfs | 0.1 cfs | 0.25 cfs |
| **Infiltration Rate (rainfall)** | 0.2 inch/hour | 0.2 inch/hour | 0.5 inch/hour |
| **Infiltration Rate (flow)** | 5.5 cfs | 0.012 cfs | -- |

*cfs = cubic feet per second

This hydromodification management plan lays out on-site and in-stream options. Projects in highly urbanized areas with more than 90 % build out and a large percentage of impervious cover are exempt. Additional information on this program is available at www.SCVURPPP.org.

## Case Study 3 – Newhall Land

Newhall Ranch is a specific plan approved for 26,000 homes in the Santa Clara watershed. Runoff from the proposed new development will be addressed by a Natural River Management Plan and a Newhall Ranch Stormwater Plan developed by the land owner.

[3] The Final HMP Report (April 2005) is available at http://www.eoainc.com/hmp_final_draft

The Natural River Management Plan is a long-term (20-year) master plan that provides for the construction of various infrastructure improvements to the Santa Clara River and tributaries. The plan maintains 15 miles of the Santa Clara River and its tributaries in a natural state with 75- to 200-foot setbacks from the river that sustains habitat quality and meets requirements for flood control. The plan calls for buried bank stabilization, instead of hardened systems, to meet county flood protection requirements and maintain habitat functions in riparian areas. Trenches have been dug far up from the streambed, filled with a compound called "sand cement" – similar to sandstone, then topped with soil, and replanted with native plant species.

The Newhall Ranch Stormwater Plan is a regional approach to storm water management that incorporates both water quality treatment and hydromodification control. The goals of this plan include:

- Reduction in percentage of impervious cover in the upper watershed using cluster design of development and maximizing open space
- Utilization of BMPs for both water quality and hydromodification source control
- Design of in-stream solutions that protect or enhance habitat.
- Incorporation of the "avoidance, minimization, mitigation" hierarchy in plan development

## Case Study 4 – Rancho Mission Viejo

Rancho Mission Viejo, a private landowner, has voluntarily developed a set of land planning principles as part of a comprehensive land-use planning and resource management program for 25,000 acres in Orange County California. These planning principles will serve as self-imposed requirements, intended to minimize the effects of future development on natural streams in planning areas. Using these principles, the landowners are proposing to focus development on ridges, which are underlain by less pervious material, thereby preserving valleys which contain pervious areas that support infiltration important to creek functions.

*Planning Principles*:

Geomorphology/Terrains

- Recognize and account for the hydrologic response of different terrains at the sub-basin and watershed scale

Hydrology

- Emulate, to the extent feasible, the existing runoff and infiltration patterns in consideration of specific terrains, soil types, and ground cover
- Address potential effects of future land use changes on hydrology
- Minimize alterations of the timing of peak flows of each sub-basin relative to the mainstem creeks
- Maintain and/or restore the inherent geomorphic structure of major tributaries and their floodplains

Sediment Sources, Storage, and Transport

- Maintain coarse sediment yields, storage and transport processes

Groundwater Hydrology

- Utilize infiltration properties of sandy terrains for groundwater recharge and to offset potential increases in surface runoff and adverse effects to water quality
- Protect existing groundwater recharge areas supporting slope wetlands and riparian zones and maximize alluvial groundwater recharge to the extent consistent with aquifer capacity and habitat management goals

Water Quality

- Protect water quality using a variety of strategies, with particular emphasis on natural treatment systems, water quality wetlands, swales, and infiltration areas

# APPENDIX C – ADDITIONAL RESOURCES

BASMAA's Start at the Source: Design Guidance Manual for Stormwater Quality Protection, 1999. Prepared by Tom Richman & Associates and CDM. Available from www.basmaa.org .

BASMAA's Using Site Design Techniques to Meet Development Standards for Stormwater Quality: A Companion Document to Start at the Source, 2003. Prepared by CDM. Available from www.basmaa.org

Better Site Design: A Handbook for Changing Development Rules in Your Community
Available for $35.00 from the Center for Watershed Protection at www.cwp.org, under the "Publications" tab.

Redevelopment Roundtable, Consensus Agreement, Smart Practices for Redevelopment and Infill Projects.
Available for free download from the Center for Watershed Protection at www.cwp.org, under the "Publications" tab; it is listed with the "Better Site Design" publications.

Builders for the Bay Program
Information about this program, which is joint project of the Alliance for the Chesapeake Bay, the Center for Watershed Protection and the National Association of Home Builders, can be found at http://www.cwp.org/builders_for_bay.htm.

The Practice of Low Impact Development
Available for $5.00 from the U.S. Department of Housing and Urban Development, at http://www.huduser.org/publications/alpha/alpha.html. It is also available for $50.00 from the NAHB Research Center's bookstore at www.nahbrc.org.

National Association of Homebuilders Research Center
"Builder's Guide to Low Impact Development" and "Municipal Guide to Low Impact Development". Available for free download from http://www.toolbase.org/tertiaryT.asp?TrackID=&CategoryID=36&DocumentID=3834

"Growing Greener: Putting Conservation into Local Codes". Available for free download from http://www.dcnr.state.pa.us/growinggreener/growinggreener.htm.

Low-Impact Development Design Strategies: An Integrated Approach; Low-Impact Development Hydrologic Analysis
Both are available for free download from US Environmental Protection Agency's website at http://www.epa.gov/owow/nps/lid/.

Truckee Meadows Structural Control Design Manual: Guidance on Source and Treatment Controls for Storm Water Quality Management - Kennedy/Jenks Consultants
http://ci.reno.nv.us/gov/pub_works/stormwater/management/controls/pdfs/TOC.pdf

National NEMO (Non Point Education for Municipal Officials) Network - Educational Materials on the link between land use and water quality
http://nemonet.uconn.edu/

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State of California
California Regional Water Quality Control Board, Los Angeles Region

**RESOLUTION NO. 2005-002**
**January 27, 2005**

**Reiteration of Existing Authority to Regulate Hydromodifications within the Los Angeles Region, and Intent to Evaluate the Need for and Develop as Appropriate New Policy or Other Tools to Control Adverse Impacts from Hydromodification on the Water Quality and Beneficial Uses of Water Courses in the Los Angeles Region**

**WHEREAS, the California Regional Water Quality Control Board, Los Angeles Region, finds that:**

1. Protecting beneficial uses within the Los Angeles Region consistent with the Federal Clean Water Act and the Porter-Cologne Water Quality Control Act (Porter-Cologne Act) requires careful consideration of projects that result in hydrogeomorphic changes and related adverse impacts to the water quality and beneficial uses of waters of the State. The alteration *away from a natural state* of stream flows or the beds or banks of rivers, streams, or creeks, including ephemeral washes, which results in hydrogeomorphic changes, is generally referred to in this resolution as a hydromodification.

2. This resolution is intended to reiterate the existing authority the Regional Board relies upon to regulate hydromodifications within the Los Angeles Region. As such, it has no regulatory effect. This resolution represents a initial step in the process of first, heightening awareness about the potential impacts of hydromodification on water quality and beneficial uses and evaluating existing laws and regulations and the current methods employed by Regional Board staff when reviewing proposed hydromodification projects and, second, strengthening, if necessary, controls and policies governing hydromodifications that negatively affect water quality and beneficial uses. As a first step, it sets forth a process to achieve one of the Regional Board's highest priorities, which is to maintain and restore, wherever feasible, the physical and biological integrity of the Region's water courses. Secondarily, maintaining the natural functions of water courses maximizes opportunities for stormwater conservation and groundwater recharge, which is very important in the semi-arid Los Angeles region where groundwater makes up half of the Region's water supply.

3. In addition to the process outlined in this resolution, the Regional Board has and will continue to strongly support restoration efforts in and along the Region's urbanized, highly modified water courses. The Regional Board also strongly supports preservation efforts geared toward ensuring long-term protection for the Region's remaining natural water courses.

4. Section 101(a) of the Clean Water Act, sets forth a national objective "to restore and maintain the chemical, physical, and biological integrity of the Nation's waters." (33 U.S.C. § 1251(a).) Chapter 1 of the Water Quality Control Plan for the Coastal Watersheds of Los Angeles and Ventura Counties (Basin Plan) recognizes this national goal and specifies that the Basin Plan is designed to implement the Clean Water Act and its goals. As a result, a regional priority of maintaining and restoring, wherever feasible, the physical and biological integrity of the Region's water courses is firmly grounded in federal and state law.

5. To realize this objective, the Clean Water Act (33 U.S.C. § 1313(c)) and federal regulations (40 C.F.R. § 131.10(a)) direct States to specify appropriate designated uses to be achieved and protected. The classification of the waters of the State must take into consideration the use and value of water for public water supplies, protection and propagation of fish, shellfish and wildlife, recreation in and on the water, agricultural, industrial and other purposes including navigation. The standards must explicitly be designed to "protect the public health or welfare and enhance the quality of the water." (33 U.S.C. § 1313(c).)

6. The Basin Plan designates the beneficial uses of the Region's water bodies consistent with the California Water Code, federal Clean Water Act, federal regulations, and with the national "fishable/swimmable" goal of the CWA forming the broad basis for the beneficial use designations of surface waters throughout the Region. Some of the beneficial uses most benefited by preserving water courses in a natural state include aquatic life [WARM and COLD among others], wetland habitat, and groundwater recharge. In addition, the Basin Plan establishes water quality objectives for the protection of these beneficial uses. An important provision of the Basin Plan, which is required by federal law (40 C.F.R. § 131.12) and state law (SWRCB Resolution No. 68-16), is an anti-degradation policy designed to maintain existing, high quality waters. The beneficial uses of water bodies, water quality objectives and anti-degradation policies, together, constitute a State's water quality standards.

7. The Regional Board primarily relies upon a three-pronged approach to regulating hydromodifications. The first two are (1) waste discharge requirements issued pursuant to Water Code section 13263 and waivers issued pursuant to Water Code section 13269 to protect waters of the State and (2) certifications issued in accordance with Clean Water Act section 401 to protect waters of the U.S. These two approaches are not mutually exclusive. (Cal. Code Regs., tit. 23, § 3857.) The third prong consists of municipal stormwater permits issued pursuant to section 402 (p) of the Clean Water Act to address stormwater related problems including stormwater quality and increased flows.

8. "Waters of the State" include all waters of the U.S. In addition, waters of the State include waters that are not "navigable waters" under the federal Clean Water Act, including certain intermittent and ephemeral streams, wetlands, lakes, reservoirs, and other isolated non-navigable waters.

9. Human civilization has attempted to alter the environment through hydromodifications for centuries. In the Los Angeles Region, beginning in the early part of the 20th century, hydromodifications were constructed by public agencies to protect residents from floods and to collect and conserve stormwater for drinking water purposes and recreation. In addition, extensive urban development, and the corresponding increase in impervious area within the watershed and decrease in the width of natural floodplains, has often resulted in significantly altered patterns of surface runoff and infiltration and, consequently, stream flow. This, in turn, has necessitated further in-stream hydromodification in order to stabilize banks and constrain the stream to the channel to prevent flooding. The sequence of events is discussed extensively in the Basin Plan and in the Regional Board's municipal storm water permit for Los Angeles County. (Regional Board Order No. 01-182.)

10. Many hydromodifications were undertaken with laudable goals often for public safety and welfare, but have later been shown to de-stabilize and enlarge stream channels as well as degrade habitat and reduce species abundance and diversity. As a result, when reviewing

hydromodification projects it is important to carefully consider whether the immediate improvements sought are designed in such a way as to avoid unintended adverse consequence on the character of the receiving water and its beneficial uses in the vicinity, and downstream of the hydromodification.

11. Activities that alter natural *stream flows* may include increasing the amount of impervious land area within the watershed, altering patterns of surface runoff and infiltration, and channelizing natural water courses. Activities that alter the natural *stream channel* include but are not limited to human-induced straightening, narrowing or widening, deepening, lining, piping/under-grounding, filling or relocating (i.e. channelization); bank stabilization; in-stream activities (e.g. construction, mining, dredging); dams, levees, spillways, drop structures, weirs, and impoundments.

12. Hydromodifications may impair beneficial uses such as warm and cold water habitat, spawning habitat, wetland habitat, and wildlife habitat in a variety of ways. Modifications to stream flow and the stream channel may alter aquatic and riparian habitat and affect the tendency of aquatic and riparian organisms to inhabit the stream channel and riparian zone. As a result of these hydromodifications, the biological community (aquatic life beneficial uses) may be significantly altered, compared to the type of community that would inhabit an unaltered, natural stream.

13. For example, channelization usually involves the straightening of channels and hardening of banks and/or channel bottom with concrete or riprap. These modifications may impair beneficial uses by disturbing vegetative cover, removing habitat; modifying or eliminating instream and riparian habitat; degrading or eliminating benthic communities; increasing scour and erosion as a result of increased velocities, and increasing water temperature when riparian vegetation is removed. The regular maintenance of modified channels may impair beneficial uses by disturbing instream and riparian habitats if not managed properly. These modifications may also, if not managed properly, impair beneficial uses by depriving wetlands and estuarine shorelines of enriching sediments or by excessive deposition in downstream environments; changing the ability of natural systems to both absorb hydraulic energy and filter pollutants from surface waters; and altering habitat for spawning and other critical life stages of aquatic organisms. Hardening of channels may also eliminate opportunities for groundwater recharge in some areas. Furthermore, some hydromodifications may reduce recreational opportunities and may reduce the aesthetic enjoyment of people engaged in recreation in and around the water body.

14. As a result of past hydromodifications, there are few natural stream systems remaining in the region. Water bodies that have not undergone extensive hydromodification such as portions of the Santa Clara River, upper San Gabriel and Los Angeles Rivers, Malibu Creek, Topanga Canyon, coastal streams in the Santa Monica Mountains, and tributaries to these larger rivers provide immeasurable benefits to the Region. These benefits include high quality warm and cold-water aquatic habitat, spawning habitat, migratory pathways, wildlife corridors, wildlife and riparian habitat, wetland habitat, recreational and aesthetic enjoyment, and groundwater recharge. Yet, many of these water bodies and their tributaries continue to be threatened by expanding urban development.

15. The Regional Board acknowledges that there is a wide array of hydromodification projects. Some result in positive environmental impacts such as stream restoration projects. Others result in negligible or temporary adverse environmental impacts if managed properly. These may include widening bridges and installing flow measuring devices, such as weirs, or energy

dissipating devices where a constructed channel meets a natural channel. On the other end of the continuum are large hydromodification projects or multiple projects with cumulative impacts that permanently alter the hydrologic and ecological functions of a stream and, thus, adversely affect the beneficial uses described above. These include, but are not limited to, projects that bury natural stream channels, channelize natural water courses, or involve instream activities such as mining or construction. Regional Board staff evaluates the severity of adverse environmental impacts on a project-by-project basis.

16. The Regional Board recognizes that maintenance activities are required in modified channels in order to ensure continued flood protection and vector control. The Regional Board has authorized such activities through the issuance of Section 401 certifications in the past and would expect to continue to authorize such activities. The Regional Board also recognizes that maintenance activities may need to be carried out on an emergency basis due to various exigencies, including brush fires and flooding. The Board through the issuance of Section 401 certifications has also authorized these emergency maintenance activities. Nothing in this resolution is intended to alter the ability of these local agencies to continue ongoing maintenance activities.

17. The Regional Board also recognizes the value of the spreading grounds that have been constructed along many of the Region's larger water courses. These spreading grounds serve a valuable function by recharging storm water into the Region's groundwater to bolster local water supplies. Nothing in this resolution is intended to alter the ability of local and regional agencies to conserve stormwater within existing regulations with the goal of increasing local water supplies.

18. The Regional Board and local agencies have undertaken or sponsored hydromodification field assessments and studies to develop peak flow design criteria to minimize or eliminate adverse impacts from urbanization for water courses in the counties of Ventura and Los Angeles. These studies include the 'Urbanization and Channel Stability Assessment in the Arroyo Simi Watershed of Ventura County, CA' (2004), and the 'Peak Impact Discharge Study' sponsored by the County of Los Angeles, which is in progress. The results from these studies will be used to develop objective criteria to reduce or eliminate the adverse impacts of hydromodification in the Los Angeles Region from new development and redevelopment.

19. Though the Regional Board does not have authority to regulate land use, the Regional Board strongly encourages land use planning agencies and developers to carefully consider, early in the development planning process, the potential impacts on water quality and beneficial uses of hydromodification projects proposed as part of new development. The Regional Board strongly discourages direct hydromodification of water courses except in limited circumstances where avoidance or other natural alternatives are not feasible. In these limited circumstances, project proponents must clearly demonstrate that a range of alternatives, including avoidance of impacts, has been thoroughly considered, hydromodification has been minimized to the extent practicable, and adequate in situ and/or off site mitigation measures have been incorporated to offset related impacts. Project proponents must also document that there will be no adverse effects to water quality or beneficial uses. This approach is consistent with the California Environmental Quality Act (CEQA), federal regulations and State and federal antidegradation policies.

20. Chapter 4 of the Basin Plan, "Strategic Planning and Implementation", outlines the suite of regulatory tools available to the Regional Board to maintain and enhance water quality. One of these tools is the 401 Certification Program. This federally required program regulates

most hydromodification projects to ensure that the projects will not violate State water quality standards of which beneficial uses are an essential component. Section 401 Certifications may include conditions to minimize impacts from hydromodification activities by implementing Best Management Practices such as working in the dry season or out of the water, among many others. Certifications may also include monitoring requirements in order to ensure that the project is completed as specified and any proposed mitigation is successful.

21. Under section 401 of the Clean Water Act, the State Water Resources Control Board and the Regional Boards have a time limit as prescribed by applicable laws and regulations, from the receipt of a complete application, to certify that a project will comply with applicable state water quality standards prior to issuance of a federal 404 dredge and fill permit for any activity that may result in a discharge to a surface water of the United States. In the event that a project will not comply with applicable water quality standards, even with all conditions proposed, then the certification may be denied. (Cal. Code Regs., tit. 23, § 3837, subd. (b).)

22. Under section 402 (p) of the federal Clean Water Act, the State Water Resources Control Board and the Regional Boards are required to issue storm water permits to owners and operators of municipal separate storm sewer systems (MS4s). On a permit-by-permit basis, MS4 permits may identify storm water-related problems and include provisions requiring municipalities to implement measures to reduce adverse impacts of hydromodification, primarily increased flows, on beneficial uses.

23. Under separate authority granted by State law (see Article 4 (commencing with section 13260) of Chapter 4 of the Porter-Cologne Act), a Regional Board may regulate discharges of dredge or fill materials as necessary to protect water quality and the beneficial uses of waters of the State by issuing or waiving waste discharge requirements, a type of State discharge permit. For projects that may result in a discharge to a surface water of the U.S., waste discharge requirements may be issued in addition to the 401 certification. (Cal. Code Regs., tit. 23, § 3857.) Issuance of waste discharge requirements may be the only option for the Regional Board in situations where the proposed discharge is to waters of the state (e.g. isolated waters, vernal pools, etc.) rather than waters of the U.S., or in situations where the federal agency does not claim jurisdiction. All discharges of waste, including dredged and fill material, to waters of the State are privileges and not rights.

24. With certain exceptions, the California Environmental Quality Act (CEQA) requires the preparation of environmental documents for all projects requiring certifications by the state or state-law-only waste discharge requirements from the Regional Board. Hydromodification activities discussed above that require certification under section 401 of the Clean Water Act or that require waste discharge requirements for dredging and filling of State waters may be subject to CEQA. For projects that may have a significant effect on the environment that cannot be mitigated, an environmental impact report must be prepared that requires consideration of feasible alternatives to the project. (Pub. Resources Code, § 21061.)

**THEREFORE, be it resolved that**

1. Maintaining and restoring, where feasible, the physical, chemical and biological integrity of the Region's watercourses is one of the Regional Board's highest priorities.

This resolution reiterates existing law and regulatory requirements and current staff practices. As such, it has no regulatory effect. However, the Regional Board directs staff to undertake a two-step process to evaluate and consider further action to control adverse impacts from hydromodification. During this process, staff is directed to involve stakeholders and regulatory agencies with jurisdiction, consistent with the requirements of the Porter-Cologne Water Quality Control Act. The first step shall be an evaluation process and shall address, at a minimum, the following:

- Prioritization for control of those hydromodification activities that cause the greatest adverse effects on water quality and beneficial uses;
- Evaluation of existing regulation of hydromodification as defined herein;
- Consideration, in light of the existing regulatory scheme, of issues affecting the Board's ability to achieve its identified objectives;
- Consideration of existing legal authorities for Board actions;
- Consideration of staff resources; and
- Evaluation and identification of the best regulatory means available to the Board and the other agencies with jurisdiction to fulfill Board objectives.

The second step shall involve, as necessary based on the above evaluation, proposals for Board consideration of actions, including without limitation educational campaigns, memoranda of understanding with other regulatory agencies, adoption of new guidance, additional municipal stormwater permit requirements or further Basin Plan amendments as necessary to address gaps in existing hydromodification control in order to maximize the Regional Board's authority to ensure that a hydromodification project does not adversely affect water quality or degrade beneficial uses of those waters.

2. Given the priority set forth in paragraph 1, the Regional Board reaffirms that the Executive Officer will only issue a certification pursuant to Clean Water Act section 401 with adequate documentation (i) that the project will comply with applicable water quality standards, including antidegradation policies, and (ii) if necessary, that adequate analysis of a range of alternatives has been performed consistent with federal regulations, the California Environmental Quality Act, and antidegradation requirements.

3. Furthermore, given the significant potential adverse impact of large-scale or multiple hydromodification projects, the Regional Board reaffirms that the Executive Officer may at his discretion choose to bring a proposed project before the Board for direction prior to certification or recommend waste discharge requirements for the proposed project, which would be subject to Board approval.

4. Given the priority set forth in paragraph 1, the Regional Board reaffirms that it will only issue waste discharge requirements with adequate documentation (i) that the WDR will implement any relevant water quality control plan, including the water quality standards contained therein, and (ii) that adequate analysis of a range of alternatives, where an alternatives analysis is required, has been performed consistent with the Porter-Cologne Water Quality Control Act, CEQA and antidegradation requirements.

5. Following completion of the two-step evaluation process described in 2 above, the Regional Board directs staff to develop, if necessary based on the conclusions of the evaluation, new policy or additional regulatory or non-regulatory tools to control adverse impacts from hydromodification, which may include educational campaigns, memoranda of understanding,

guidelines, additional municipal stormwater permit requirements and amendments to the Basin Plan.

Regulatory tools may incorporate specific criteria and evaluation requirements to be used by Regional Board staff when evaluating projects for water quality certification or waste discharge requirements, and setting conditions for certification or for Standard Urban Stormwater Mitigation Plan (SUSMP) or Stormwater Quality Urban Impact Mitigation Plan (SQUIMP) approval by the local agency. If a Basin Plan amendment is necessary, the Regional Board further directs staff to bring said amendment to the Board for its consideration in the near future. Any proposed criteria and evaluation requirements should ensure that developers avoid, minimize or, as a last course, compensate for both the on-site and downstream adverse impacts of development on the water quality and beneficial uses of watercourses.

6. When evaluating the issue of hydromodification and identifying specific actions to be taken if necessary, the Regional Board shall consider at a minimum the following:

- Existing federal and state law and regulation; state and regional policies; and current methods employed by Regional Board staff related to hydromodification of water courses.
- Consistency and coordination with other agencies' authorities over hydromodifications.
- Existing staff resources available to implement current Regional Board programs and regulations related to hydromodification of water courses.
- The local and regional value of maintaining water courses in their natural state.
- Federal guidelines including, but not limited to, section 404(b)(1), which constitutes the substantive federal environmental criteria that are used in evaluating applications for certain discharges of dredge or fill material;
- Statewide General Waste Discharge Requirement for certain dredge and fill activities not requiring a Section 404 Permit or a Section 401 Certification under the federal Clean Water Act (State Water Resources Control Board Water Quality Order No. 2004-0004-DWQ);
- State Water Resources Control Board, "Regulatory Steps Needed to Protect and Conserve Wetlands not subject to the Clean Water Act," Report to the Legislature, Supplemental Report of the 2002 Budget Act, April 2003.
- The State Water Resources Control Board Workplan: Filling the Gaps in Wetlands Protection (Sept. 24, 2004);
- State Water Resources Control Board Guidance for Regulation of Discharges to "Isolated" Waters (June 25, 2004);
- National Research Council, "Riparian Areas: Functions and Strategies for Management, Committee on Riparian Zone Functioning and Strategies for Management," National Academy Press, Washington, D.C., 2002.
- State guidance including, but not limited to, "A Primer on Stream and River Protection for the Regulator and Program Manager" (by Ann L. Riley) and the "California Rapid Assessment Method for Wetlands" for evaluating mitigation sites;
- "Stream Corridor Restoration: Principles, Processes, and Practices." Prepared by the Federal Interagency Stream Restoration Working Group (FISRWG) (10/1998);
- General principles of low impact development (various sources);
- The findings of the study commissioned by the Los Angeles County Department of Public Works through the Storm Water Monitoring Coalition in order to satisfy a requirement of the Los Angeles County Municipal Storm Water Permit (Regional Board Order No. 01-182), which calls for a study to evaluate peak flow control and determine numeric criteria to prevent or minimize erosion of natural stream channels and banks caused by urbanization, and to protect stream habitat;

- The findings of the study "Urbanization and Channel Stability Assessment in the Arroyo Simi Watershed of Ventura County, CA – Final Report" (2004) completed by the Ventura County Watershed Protection District, in order to satisfy a requirement of the Ventura County Municipal Storm Water Permit (Regional Board Order No. 00-108), which calls for the development of criteria to prevent or minimize erosion of natural channels and banks caused by urbanization and protect stream habitat; and
- Additional data collected or initiated by municipalities, dischargers and developers on stream stability for study sites in Los Angeles and Ventura Counties to reduce statistical uncertainty and/or improve model predictability when establishing stream stability protective criteria.

7. If a Basin Plan amendment is deemed necessary, staff is directed to consult with affected state and local agencies prior to formulating the draft amendment(s).

8. During the evaluation process, staff is directed to seek input from:

- the Department of Fish and Game and the U.S. Army Corps of Engineers, the United States Fish and Wildlife Service and other agencies with jurisdiction over hydromodification projects to ensure that any future policies and requirements to be proposed do not conflict with the jurisdiction and regulatory authority of these agencies; and
- stakeholders, including flood control agencies, agricultural interests, the building and construction industry, and environmental groups.

9. Pursuant to section 13224 and 13225 of the California Water Code, the Regional Board, after considering the entire record, including oral testimony at the hearing, hereby adopts the Resolution.

I, Jonathan Bishop, Executive Officer, do hereby certify that the foregoing is a full, true, and correct copy of a resolution adopted by the California Regional Water Quality Control Board, Los Angeles Region, on January 27, 2005.

*ORIGINAL SIGNED BY* *2/23/05*

Jonathan S. Bishop, P.E.
Executive Officer

Date

*Final Version*

# USING CONCEPTS OF WORK TO EVALUATE HYDROMODIFICATION IMPACTS ON STREAM CHANNEL INTEGRITY AND EFFECTIVENESS OF MANAGEMENT STRATEGIES

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## ABSTRACT

Urbanization modifies the natural watershed and stream hydrologic and geomorphic processes by altering the landscape and introducing impervious surfaces and drainage infrastructure. Increases in volume, frequency, and duration of runoff from urban development are defined as hydromodification. Hydromodification intensifies sediment transport and leads to stream bank erosion and channel incision. The Santa Clara Valley Urban Runoff Pollution Prevention Program (Program) is required to develop a Hydromodification Management Plan (HMP). As part of developing the HMP, the Program in cooperation with the Santa Clara Valley Water District, developed and tested a method for predicting channel instability, and is in the process of establishing in-stream stability criteria, runoff control design criteria, and management measures, which include a combination of on-site, in-stream, and regional control strategies. The method predicts erosion potential (Ep) using an index representing the effective work done by flow energy in excess of the amount required to transport the available sediment load. The predicted Ep was compared to observed conditions in a test watershed and found to accurately predict stable and unstable channel conditions. A "threshold of adjustment" is identified that distinguishes between stable and unstable conditions. The Ep and threshold of adjustment are intended to be used to set management criteria and evaluate effectiveness of proposed solutions. The Ep concept also has been used to evaluate the effectiveness of control strategies.

## INTRODUCTION

It is well documented that urbanization modifies the natural watershed and stream hydrologic and geomorphic processes by introducing impervious surfaces and drainage infrastructure into a watershed (GeoSyntec, 2002; Bledsoe & Watson, 2001; Booth, 1990; Hollis, 1975; Hammer, 1972). Hydromodification is defined as increases in surface runoff volume, frequency and duration resulting from development (GeoSyntec 2002). Hydromodification intensifies sediment transport and often leads to stream channel enlargement and loss of habitat and associated riparian species (GeoSyntec, 2002; Bledsoe & Watson, 2001; Booth, 1990; MacRae, 1992).

The California Regional Water Quality Control Board (RWQCB) San Francisco Bay Region, under the National Pollutant Discharge Elimination System permit program for stormwater, is requiring dischargers to address the impacts from hydromodification. The Santa Clara Valley Urban Runoff Pollution Prevention Program (SCVURPPP) is one of the first stormwater programs subject to the new permit requirements, which includes the development of a Hydromodification Management Plan (HMP). This paper summarizes the technical study supporting the development of the HMP.

There have been many facets of this study that could be the focus of a paper. The goal of this paper is to summarize the approach (which has been published in recent conference proceedings), but focus on the *work* concepts used to predict hydromodification impacts and describe how these concepts are used to make management decisions and develop a watershed-wide standard. The development of the HMP began by preparing a Work Plan that was reviewed and accepted by the RWQCB followed by an in-depth literature review of the issues regarding hydromodification, methods of analysis, and potential management strategies. An Expert Panel of three university professors reviewed and commented on this work.

The permit requires a management plan that encompasses the full Santa Clara Valley Basin; however it is too costly to evaluate every stream system in the Basin. The Thompson Creek subwatershed was selected as a test watershed located in the south-eastern portion of the Basin (Figure 1). It is assumed that Thompson Creek will be representative of the entire eastern side of the Basin because the climate, physiography, soils and vegetation are similar.

The study area is 26 square miles upstream from a flow gage at Quimby Road, and includes five primary tributaries, which drain the east side Diablo Range (Figure 2). Historically, the tributaries did not directly connect to Thompson Creek, but discharged onto their alluvial fans, dropping any sediment load. Overland flow migrated north-westerly toward a natural topographic depression that is now Lake Cunningham infiltrating into the valley floor along the way. The study area has experienced rapid development in the last 25 years as agricultural land was converted to residential and commercial properties. During this period, the stream experienced rapid channel enlargement, including stream bed incision and bank failures. Local agencies designed and installed grade control structures in response to channel adjustments.

## LITERATURE REVIEW

This section provides a brief overview of the literature review as it pertains to the concepts of work and channel adjustment. Over 50 articles were reviewed that discuss: 1) the natural hydrologic and geomorphic process important to address hydromodification, 2) the effects of urbanization on hydrology and geomorphology, 3) assessment tools that can be used to address hydromodification, and 4) management strategies used to implement the HMP.

Early research in the 1970's showed that urbanization significantly alters the frequency and duration of natural runoff events especially for smaller more frequent storms (Hollis, 1975; Hammer 1972). Hollis (1975) concluded that the increase in runoff for flows with a frequency of 1 to 2-years and smaller, increased as much as 20 times. Flow changes of this type initiate long-term adjustments in stream morphology and channel enlargement is the most common response (Booth, 1990). MacRae et al. (1993) showed that increases in the frequency of the mid-bankfull to bankfull flow range caused the greatest increase in erosion. Bledsoe and Watson (2001) reported that the frequency of scouring events increased by factors of 2.5 to 5 for two watersheds they studied.

Booth (1990) suggested that stream power is a reasonable measure to distinguish between eroding and non-eroding channels.. Stream power however, does not incorporate channel geometry or the boundary materials' ability to resist erosion, nor does it account for the duration that flows persist at these rates. Bledsoe and Watson (2001a) stated that the best indicators of stability involve a ratio of the erosive forces to the resisting forces. MacRae (1993, 1996) developed an index that includes a measure of the most sensitive boundary material's erodibility. MacRae (1993, 1996) suggested that the erosion potential for the channel boundaries should remain the same between developed and undeveloped land use conditions. A discharge control strategy that maintains the same erosion potential provides the closest reproduction of pre-development conditions and best protection of the stream's beneficial uses.

## STUDY APPROACH

The study is subdivided into five primary elements: 1) problem area and reach characterization, 2) geomorphic assessment, 3) hydrologic modeling, 4) stability assessment, and 5) effectiveness evaluation of solutions. Figure 2 presents a map of the study area and cross section locations where the analysis was performed.

Problem area and reach characterization describes features of the watershed and stream channels necessary to understand the nature and extent of the problem and to explain existing conditions. Historical aerial photography, soils and geologic maps, channel maintenance records, infrastructure data and historical surveys were used to distinguish between urbanizing impacts and impacts caused by past land use practices.

The geomorphic assessment describes the geologic and geomorphic characteristics of the stream network, the dominant physical processes that seem to be controlling stream attributes and erosion, and the extent and modes of failure for observed eroding channel banks and beds. Field crews recorded reach-wide observations on streambed and bank erosion, collected location specific data at 37 cross sections, and then assigned each location a rank of *stable, low, medium or high* observed condition of erosion, or likelihood of erosion in the near future. Several factors affecting channel bank and bed stability were combined with the extent, age, and magnitude of existing erosion to designate an appropriate erosion ranking.

A hydrologic continuous simulation model of the pre-project, existing, and future (year 2020) land use conditions was developed using the U.S. Army Corps of Engineers' Hydrologic Engineering Center - Hydrologic Modeling System (HEC-HMS). The model was calibrated using two years of measured flow data. The calibrated model was run using 50 years of rainfall record and produced a time series of hourly stream flows to analyze changes flow duration, runoff volume, and frequency between land use scenarios. The soil moisture accounting module was used to incorporate the affects of antecedent conditions.

The stability assessment is based on the premise that a balance among flow energy, sediment loads, and channel resilience exists naturally and should be maintained in order for the stream network to remain stable (GeoSyntec, 2002; McRae, 1996). The hypothesis is that, over time, the stream channel slope and geometry co-evolved with vegetation, local physiography and climate to establish its pre-development dynamic equilibrium. To maintain stream channel stability, the management goal is to maintain the pre-development flow energy, sediment transport and erosion characteristics.

An *index* representing the *total effective work* done on the channel boundary was derived that predicts the likelihood of channel adjustment given watershed and stream hydrologic and geomorphic variables. The index under urbanized conditions is compared to the index under pre-urban conditions expressed as a ratio (Ep). An empirical relationship between Ep and the observed channel erosion is derived and used to make informed decisions.

The effective work index ($W$) is computed as the excess shear stress that exceeds a critical value for streambed mobility or bank material erosion integrated over time and represents the total work done on the channel boundary:

$$W = C \cdot \sum_{i=1}^{n} (\tau_i - \tau_c)^{1.5} \cdot V \cdot \Delta t_i \qquad (1)$$

Where $C$ = constants and unit conversions, $\tau_c$ = critical shear stress that initiates bed mobility or erodes the weakest bank layer, $\tau_i$ = applied hydraulic shear stress, $\Delta t$ = duration of flows (in hours), and $n$ = length of flow record. The effective work index for presumed stable stream channels under pre-urban conditions is compared to stable and unstable channels under current urbanized conditions. The comparison, expressed as a ratio, is defined as the Erosion Potential (Ep) following McRae (1992, 1996).

$$Ep = \frac{W_{post}}{W_{pre}} \qquad (2)$$

where:

$W_{post}$ = work index estimated for the post-urban condition
$W_{pre}$ = work index estimated for the pre-urban condition

A "threshold of adjustment" is considered that distinguishes between stable and unstable conditions. The Ep and the threshold of adjustment are used to set management criteria and evaluate the effectiveness of proposed solutions (McRae, 1993).

## RESULTS

### GEOMORPHIC ASSESSMENT

The project team distinguished six hydrographic segments based on stream flows from large urban outfalls. Each segment has similar stream discharges and reflects important differences in channel flows. Table 1 lists the hydrologic and geomorphic conditions observed in the field.

*Channel Geometry and Slope*: Channel width and depth are extremely variable, with width generally differing by 4 to 5 times and depth by 2 to 3 times between cross sections. Segment 5 shows a rapid transition in channel geometry because changes from stable to unstable channel conditions are located within this segment. Channel slopes range by an order of magnitude (0.002 to 0.025 ft/ft) varying by cross-section throughout the reach.

*Bank Material*: Channel banks are not homogenous; instead they consist of multiple layers with different sediment characteristics that vary through the subwatershed. Thompson Creek is generally dominated by cohesive banks that are fairly resistant to erosion.

Segments of the creek have exposed hardpan in various locations. Layers of moderately to well-sorted sands and gravels with some silt and clay often represented the weakest portion of the bank. Widespread undercutting often occurred at the weaker alluvial layer.

*Bed Material*: The channel bed is generally composed of gravel with some sand. The median grain size (D50) ranged from 3.2 to 10.2 millimeters. The median grain size falls within the very fine to medium size gravel class. This allows use of the average critical shear stress and velocity for the bed. The average values for critical shear stress and critical velocity are 0.14 lbs/sq-ft and 2.8 ft/sec, respectively.

*Erosion Classification*: Erosion rankings of *stable, low, medium,* or *high* were assigned to each cross-section. These rankings were qualitative in nature and no numerical standard was applied. Instead, all factors affecting bank and bed stability (slope, undercutting, bank slope, type and density of vegetation, obstructions) were combined with the observed extent, age, and magnitude of observed erosion to designate the rank. Cross-sections that received a rank of *high* were severely incised reach-wide or actively incising with eroding banks, either through processes of undercutting, shearing and/or slumping. Channel banks were generally vertical and bare with vegetation stabilizing only the tops of banks. Eleven of the thirty-seven cross-sections were assigned *high*. Cross-sections designated as *low* had banks that were not eroded or eroded but now stable. *Low* ranking cross-sections generally had gentler slopes and denser vegetation, and sometimes located behind grade control structures where the bed had aggraded. Cross-sections ranked as medium had characteristics in between those described for *high* and *low*. Thirteen of thirty-seven cross-sections were designated as *medium* and thirteen designated as either *low* or *low* to *medium*. A rank of *stable* was assigned to three upstream sections.

STABILITY ASSESSMENT

Figure 3 presents a histogram of the pre-urban and post-urban flow records, which expresses the number of hours (i.e., flow duration) that flows occur within each discrete flow range. This figure shows that flow duration increases 2 to 3 times in the high flow range, and 20 to 30 times in the low flow range, between pre- and post- development scenarios. Runoff volume increases are also significant.

*Effective Work Curves*: Both incremental and cumulative work curves were generated and evaluated for both pre- and post-development. Figure 4 presents the cumulative curves for section TC1-6, in Segment 1 as an example. These curves illustrate which flows are doing the greatest amount of work on the stream channel and what flows have the greatest increase in work as a result of development. These results show that the greatest increase in work is done by flows less than the 2-year peak flow magnitude. Flows less than the 2-year peak flow magnitude have the greatest increase in frequency and runoff volume, and ultimately the greatest increase in energy to transport sediment and erode channel boundaries. These results also showed that approximately 95 percent of the total work is done by flows less than the 10-year peak flow magnitude. This information is used to target the appropriate flow range for management purposes.

**Table 1. Hydraulic & Geomorphic Characteristics of Thompson Creek**

| Cross-section | W/D Ratio [2] | Channel Slope | $D^{50}$ [3] | Exposed Clay Hardpan? | Depth of Mobile Material | Weakest Bank Material (left bank)[4] | Weakest Bank Material (right bank)[4] | Erosion Ranking (H,M,L)[5] |
|---|---|---|---|---|---|---|---|---|
| | *(unitless)* | *(feet/feet)* | *(mm)* | *(Y/N)* | *(in)* | | | |
| **Segment 1** | | | | | | | | |
| TC1-1 | 3.9 | 0.0016 | 5.8 | N | 24 | sandy gravel | silty loam and gravel | L |
| TC1-2 | 4.3 | 0.0040 | - | Y | 3-4 | silt loam | sand and small gravel | L |
| TC1-6 | 4.5 | 0.0102 | 4.5 | N | 12-24 | Sandy loam with gravel | gravelly sand | M |
| TC1-7 | 3.2 | 0.0091 | - | N | 12 | silt loam with gravel/sand | silty loam with gravel/sand | M |
| **Segment 2** | | | | | | | | |
| TC2-1 | 3.4 | 0.0078 | - | N | 18 | loamy clay | loamy clay | M-H |
| TC2-2 | 3.0 | 0.0160 | - | N | 10 | Clayey sand-gravel | clayey sand-gravel | L-M |
| TC2-3 | 3.5 | 0.0109 | - | N | 12 | Clayey sand-gravel | clayey sand-gravel | H |
| TC2-5 | 3.9 | 0.0117 | 4.0 | N | > 24 | silt, sand and some clay | sandy silt | M |
| TC2-6 | 4.0 | 0.0150 | - | N | 10 | well sorted med sand | clayey sand and gravel | M |
| TC2-8 | 3.5 | 0.0013 | - | N | 6 | Sand and gravel | fine sand | H |
| TC2-9 | 3.6 | - | - | N | 7 | colluvium | fine sand w/ some clay | L |
| TC2-10 | 4.5 | 0.0064 | 3.2 | N | - | sand-gravel-silt w/ clay | sand-gravel w/ some clay | M |
| **Segment 3** | | | | | | | | |
| TC3-1 | 4.3 | 0.0032 | - | N | 24 | sand | silty loam | L-M |
| TC3-2 | 5.6 | 0.0031 | - | N | 24 | silty-sandy loam | silty loam w/ pebbles | L |
| TC3-3 | 3.7 | 0.0045 | 5.0 | N | 24 | silty loam w/ gravel | silty fine gravelly loam | L-M |
| TC3-4 | 2.7 | 0.0084 | - | N | 24 | clayey pebbly with silt loam | sandy gravelly loam | M |
| TC3-5 | 5.3 | 0.0099 | - | N | - | silty sandy loam | gravelly silty loam | H |
| TC3-6 | 3.3 | 0.0086 | | Y | 24 | sandy gravelly loam | gravelly loam | H |
| TC3-7 | 3.8 | 0.0094 | 6.9 | N | 18 | silty loam with some gravels | silty loam with some gravels | L |
| **Segment 5** | | | | | | | | |
| TC5-1 | 3.9 | 0.0250 | - | N | 9.6 | sand and gravel with silt | silty sand w/ some gravel | H |
| TC5-2 | 2.7 | 0.0058 | 9.0 | N | >24 | silty sand and gravel | silty sand and gravel | M |
| TC5-3 | 1.5 | 0.0047 | - | N | 12 | Silts and sands | fine sand and silt | H |
| TC5-4 | 3.2 | 0.0166 | - | N | >24 | clayey sand and gravel | sandy silt | H |
| TC5-5 | 5.2 | 0.0102 | 3.7 | N | >>24 | Pebbly sand and silt | sand, pebbly sand | M-H |
| TC5-6 | 5.2 | 0.0086 | 8.0 | N | 12 | well sorted sand | sand and gravel | S |
| TC5-7 | 7.8 | 0.0129 | 3.5 | N | >24 | clayey sand and gravel | clayey sand and gravel | S |
| **Segment YB** | | | | | | | | |
| YB1-0 | 4.7 | 0.0222 | - | N | 24 | pebbly silty loam | pebbly silty loam | S |
| YB1-1 | 2.3 | 0.0179 | 10.2 | N | 12 | silty pebbly loam w/ gravels | silty pebbly loam w/ gravels | M |
| YB1-2 | 3.5 | 0.0282 | - | N | 12 | silty pebbly loam | silty pebbly loam | M |
| YB1-3 | 3.1 | 0.0221 | - | N | 24 | silty pebbly loam w gravels | silty pebbly loam | M |
| YB1-4 | 5.1 | 0.0111 | - | N | 24 | silty loam -- gravelly cobbly | gravelly cobbly loam | L |
| YB1-5 | | - | - | Y | 12 | cobbly, silty, pebbly loam | cobbly, silty, pebbly loam | L |
| YB1-6 | 1.2 | 0.0139 | | Y | 12 | clay-silty gravelly-cobbly | clayey-gravelly loam, silty | H |
| YB1-7 | 11.0 | 0.0149 | 4.8 | N | 24 | silty gravelly loam | silty gravelly loam | M |

*Erosion Potential (Ep)*: Figure 5 presents an Erosion Potential Chart with Ep plotted for each section sub-divided by the field designated erosion classification. Only a subset of the results is shown for clarity. There is a good correlation between the observed erosion classification and the magnitude of the computed Ep. An Ep ratio of 2 means that the post-urban runoff condition exerts 2 times more total work on the channel boundary then under the pre-urban condition. Ep ratios range from less than 1 to 10. Interestingly, some sections that fall below Ep=1 were observed in the field as potentially aggrading.

One of the objectives was to identify a *threshold* that could be used to define management strategies and discharge limitations. Figure 6 presents a probability curve using a Logistic Regression technique on the data presented in Figure 5. This technique relates the probability of having unstable channel conditions to the computed Ep (Bledsoe and Watson, 2001b). For example, given a computed Ep of 2, the likelihood of having unstable conditions is about 20 percent. The probability curve can also be used to select an Ep threshold by specifying a level of acceptable "risk" (i.e., probability that a stream channel is not stable). For example, to accept a 10% "risk", the Ep threshold would be 1.2. The effectiveness of management strategies and BMP's are evaluated by their ability to maintain the Ep below the threshold of 1.2.

## MANAGEMENT STRATEGIES

Stormwater management strategies that were considered include pre- and post- runoff volume matching, hydrograph matching, flow duration matching, and managing effective work through the erosion potential (Ep). Various combinations of BMPs can be used including on-site or project based controls, larger scale regional controls, and in-stream controls that modify the stream to accept the changed watershed hydrology. Results to date indicate that flow duration matching is a protective management strategy that can apply to on-site or project based controls which has the benefit of not requiring additional information on instream hydrology and stability. Ep control is more applicable to watershed wide master planning involving regional and instream controls and possibly for very large developments.

It was originally thought that practical implementation could be achieved by allowing smaller developments to perform simpler calculations, such as discrete event volume control or hydrograph matching. However, after further study, the simpler methods are not proving to be adequate to protect stream channels from hydromodification because of the cumulative nature of smaller but erosive flows.

Volume control means that only the amount of runoff generated from the pre-urban site may be discharged from the site after development, and the difference in volume must be retained on-site or discharged to some other out-of-stream facility such as a by-pass. Our analysis found that specifying volume control alone would not be protective and could lead to increases in work and stream erosion. This is because post-urban runoff is discharged at higher rates of flows due to increases in impervious surfaces. Volume control alone does not account for the differences in erosive power for the same volume at higher flows as compared to lower flows.

To improve volume control, one management approach would be to require "hydrograph matching". Hydrograph matching maintains the volume and distribution of flows for a single discrete storm event (e.g., the discharge from the flow control facility for, say, a 10-year storm must match the pre-development runoff hydrograph shape and volume for that storm). Hydrograph matching was tested by designing a control basin to maintain the design event hydrograph shape and volume and then evaluating the basin's effectiveness at maintaining the pre-urban work. Design storms used included the 2-, 10-, and 50-year hydrographs. The analysis found that hydrograph matching would not adequately maintain the in-stream erosion potential for the full range of flows.

Flow duration control is an extension of volume control but is more accurate for sizing controls because matching flow duration maintains runoff volume for the full distribution of flows. When one matches the pre-urban flow duration curve, the total number of hours that flows persist at any given magnitude is maintained and thus work is maintained. Flow duration control can be used on-site or for mixed regional solution strategies. Flow duration control was found to be effective at maintaining the erosion potential of the stream.

Although flow duration control is an effective management strategy, a more comprehensive approach is to perform an Ep analysis and directly compute the erosion potential in-stream. In addition to evaluating hydrologic modifications, the Ep method can be used to distinguish between more or less resilient stream channels, identify critical stream reaches, and used to design in-stream solutions that modify channel characteristics to accept the new hydrologic regime.

The Ep methodology was used to test the effectiveness of in-stream modifications and found to be a good tool for designing effective restoration projects. The Ep methodology can measure the effect of changing channel slope, geometry, roughness, and resistance from armoring (e.g., biotechnical solutions). The Ep method predicted stable slopes consistent with the results using regime equations and with measured slopes in undeveloped watersheds around the Bay Area. Biotechnical solutions can substantially increase the apparent critical shear stress of the channel boundary from 0.14 lbs/sf to 1.6 lbs/sf or larger, and the Ep can be reduced to within the threshold of 1.2.

## CONCLUSIONS

All conclusions specifying a numeric value apply to Thompson Creek and the eastside Santa Clara Valley, and would not necessarily apply to other watersheds outside this region.

1. Hydromodification and associated channel enlargement are best addressed as the long-term cumulative process of frequent erosive flows, as opposed to using discrete event methods.
2. Urbanization significantly increased the duration and erosion potential of small to moderate size flows more than those for larger flows. The incremental work associated with geomorphically significant flows for post-urban conditions exceeds the pre-urban case by as much as 20 to 30 times.
3. The effective work index ($W$) distinguishes between stable reaches (pre-urban, stable/low existing conditions), and unstable reaches (medium/high existing conditions).
4. The Ep Chart and Logistic Regression show a strong indication of a *threshold of adjustment* and express the likelihood or "risk" of channel instability from hydromodification. An Ep threshold of 1.2 is associated with a 10 percent likelihood of causing stream channel erosion and enlargement. An Ep threshold of 1.2 has been selected for effectiveness tests, management and designs.
5. The Ep methodology is best used to address cumulative watershed scale modifications in land use and hydrology during master planning or for larger scale development projects.
6. Ep can be used to evaluate the effectiveness of hydromodification management strategies, including on-site, regional, in-stream projects, or a mix of strategies.
7. Matching runoff volume or design storm hydrographs for single events, such as the 2-year event, is not protective of streams at risk from hydromodification, and should not be used as management strategies.

8. Matching pre- and post-urban flow duration curves is the best management strategy for design of on-site and regional BMP's when limited watershed or stream hydro-geomorphic data are available.

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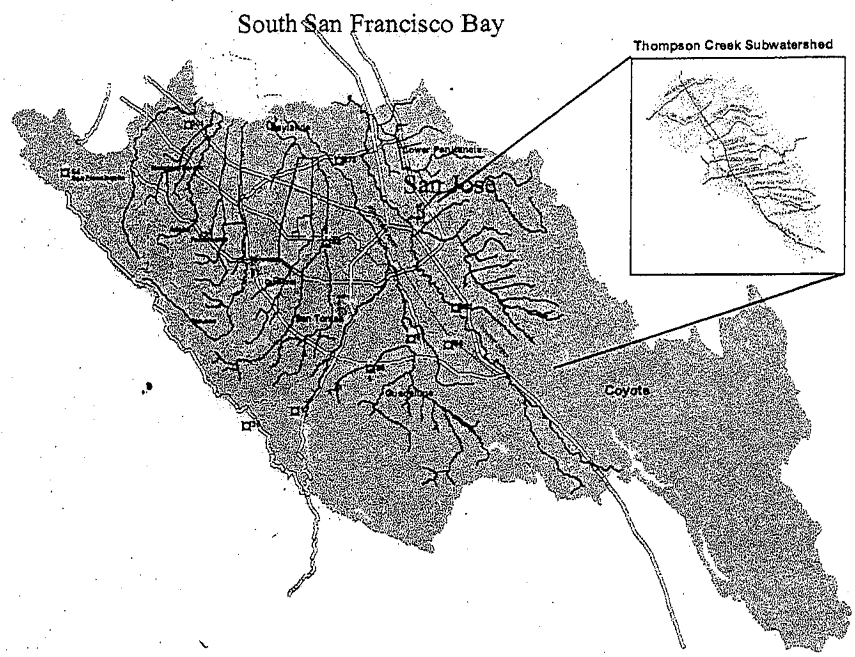


**Figure 1. Santa Clara Valley Basin and Thompson Creek Study Area**

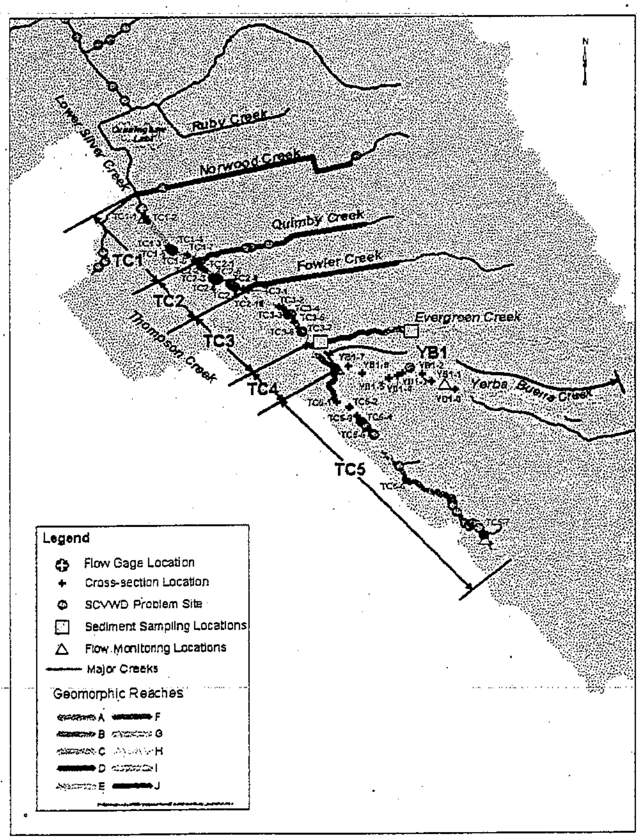


**Figure 2. Thompson Creek Study Area Characteristics**

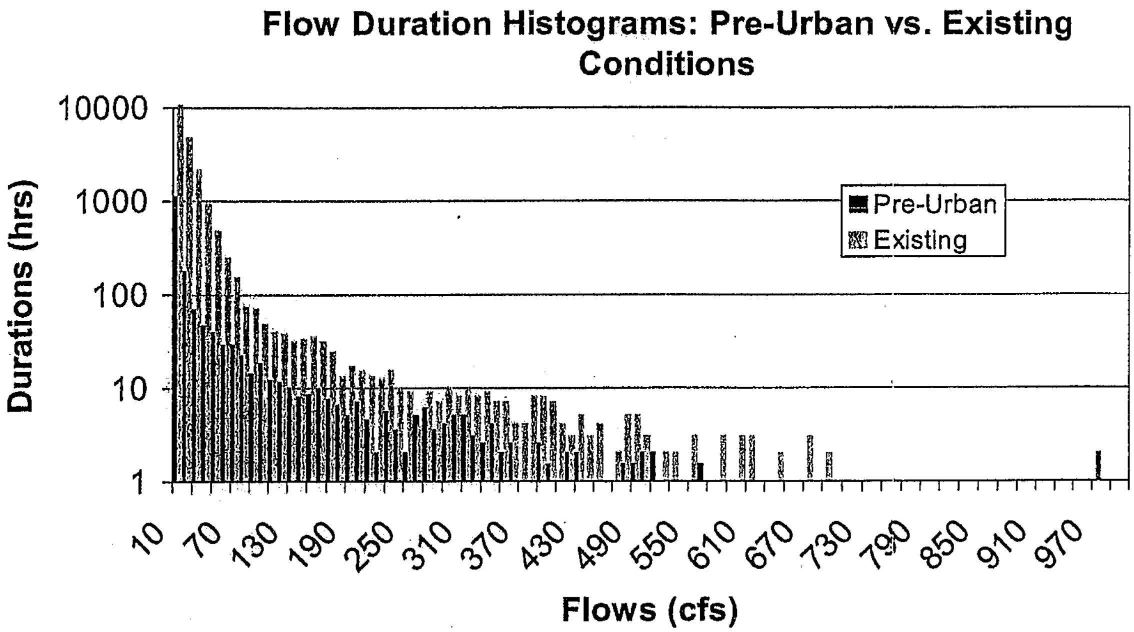


**Figure 3. Histograms for pre-urban and existing conditions**

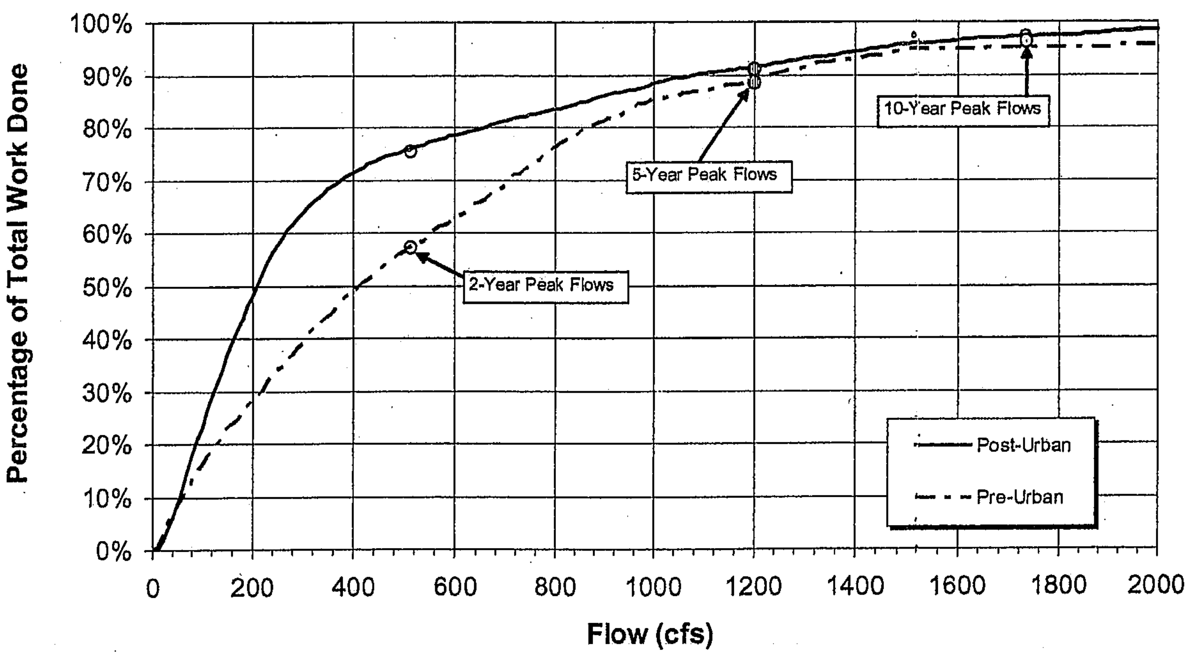


**Figure 4. Cumulative Work Curves for Segment 1, TC1-6**

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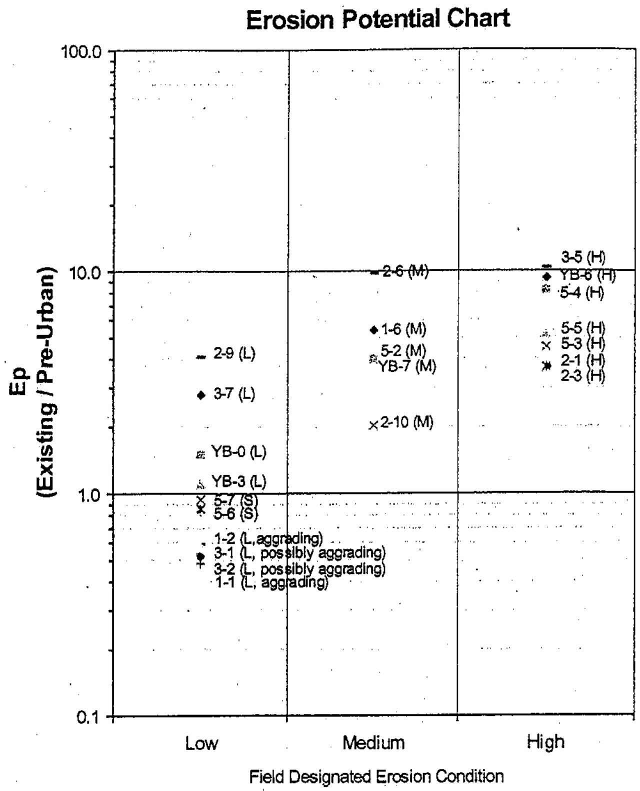



**Figure 5. Erosion Potential Chart illustrating Ep for each cross-section based on erosion classification (low, medium and high)**

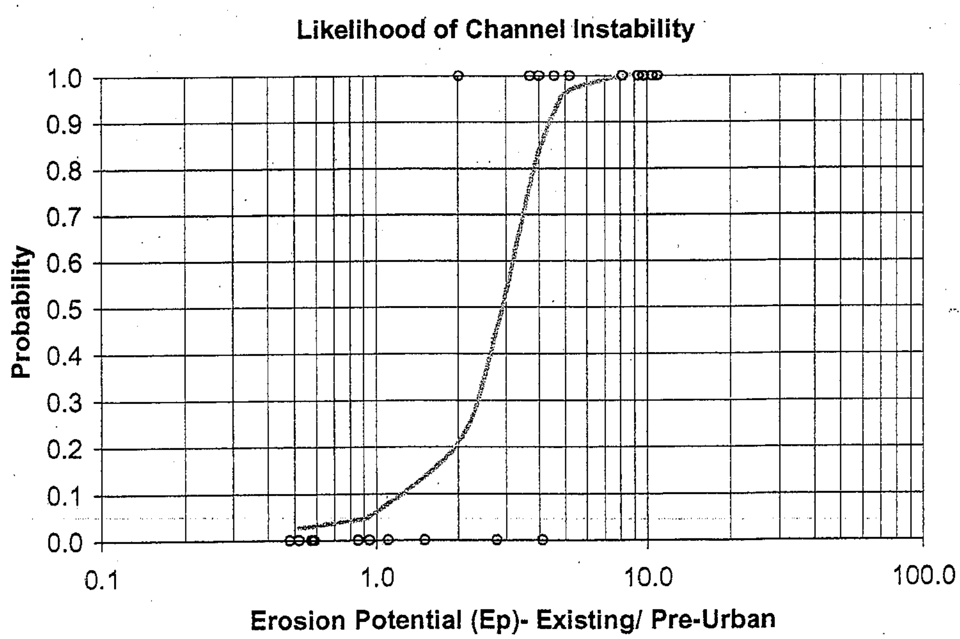



**Figure 6. Probability curve of the Ep using a Logistic Regression**


# SANTA CLARA VALLEY And Other HYDROMODIFICATION MANAGEMENT STUDIES

By

Gary Palhegyi
GeoSyntec Consultants

A005480

# Overall Approach for the SCVURPPP HMP

- Develop problem statement, define goals & objectives
- Characterize the watershed and stream system, develop a conceptual model
- **Conduct literature review**
- **Develop an assessment method to reliably predict stream instability & evaluate controls**
- **Define design criteria, control measures and management strategies**
- Convene Expert Panel, Involve the public

# Literature Review

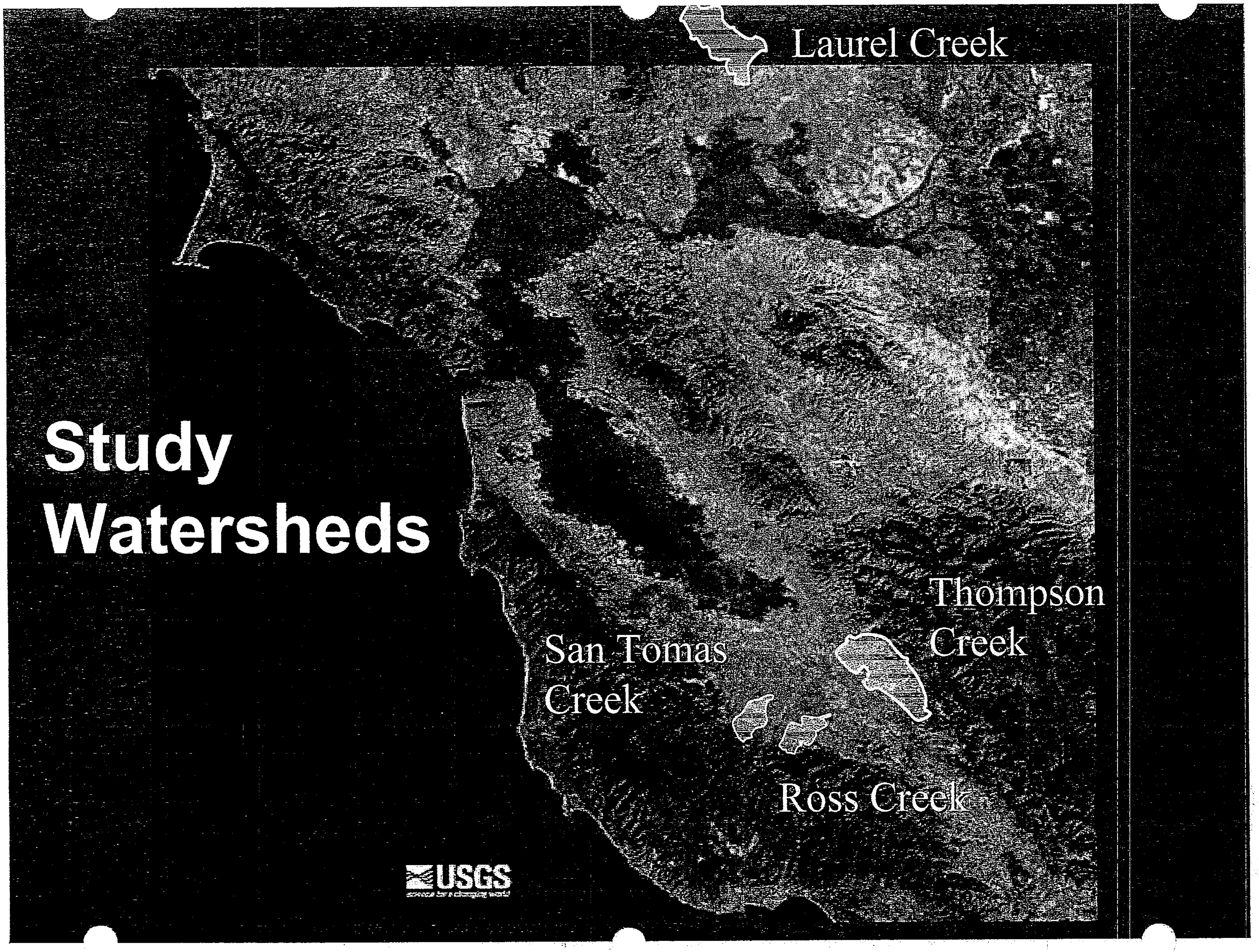
- Link watershed and development characteristics with channel hydraulics and channel resilience
  - Local variation in runoff, slope, geometry, bed and bank materials, vegetation
- Channel stability is a function of continuous hydrologic and geomorphic processes
- Time integrated metrics provide the closest reproduction of these processes
- Management strategies should consider the full range of geomorphically significant flows

# Developing & Verifying the Assessment Methodology

Predict future impacts
Evaluate control strategies

Pre-Urban        Existing        Future

Develop/test method


Study
Watersheds
Laurel Creek
Thompson
Creek
San Tomas
Creek
Ross Creek
USGS

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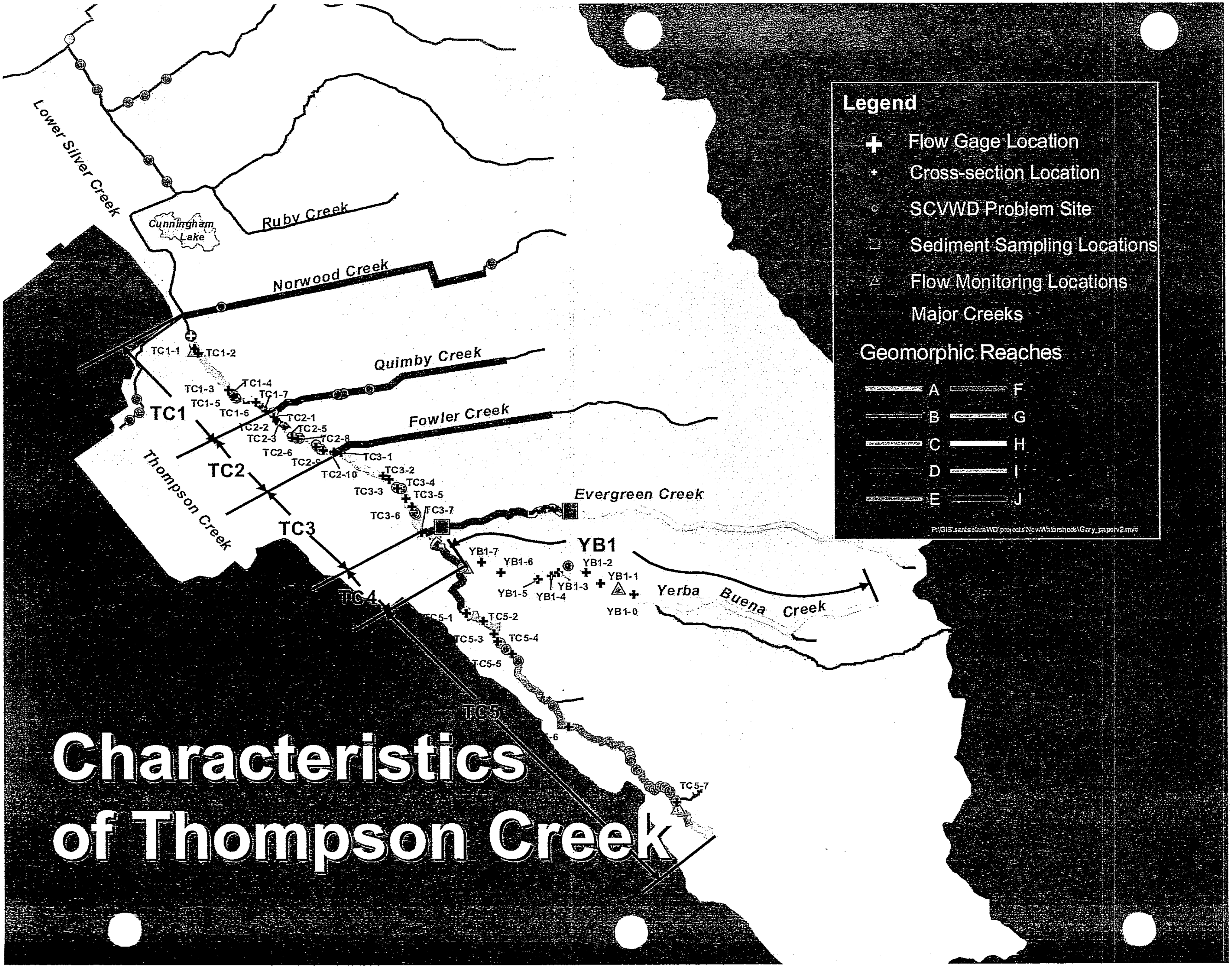
# Elements of the Assessment Methodology

- Characterize Watershed and Streams
  - History, climate, geology
- Geomorphic Assessment
  - Surveys, bed/bank, failure mechanisms
  - Classify as “stable, low, medium, high
- Hydrology Modeling
  - Calibrated
  - 50 year continuous simulation
- Stability Assessment


Characteristics of Thompson Creek
Legend
Flow Gage Location
Cross-section Location
SCVWD Problem Site
Sediment Sampling Locations
Flow Monitoring Locations
Major Creeks
Geomorphic Reaches
A
B
C
D
E
F
G
H
I
J
Lower Silver Creek
Ruby Creek
Cunningham Lake
Norwood Creek
Quimby Creek
Fowler Creek
Evergreen Creek
Thompson Creek
Yerba Buena Creek
TC1
TC2
TC3
TC4
TC5
YB1
TC1-1
TC1-2
TC1-3
TC1-4
TC1-5
TC1-6
TC1-7
TC2-1
TC2-2
TC2-3
TC2-5
TC2-6
TC2-8
TC2-10
TC3-1
TC3-2
TC3-3
TC3-4
TC3-5
TC3-6
TC3-7
TC5-1
TC5-2
TC5-3
TC5-4
TC5-5
TC5-7
YB1-0
YB1-1
YB1-2
YB1-3
YB1-4
YB1-5
YB1-6
YB1-7

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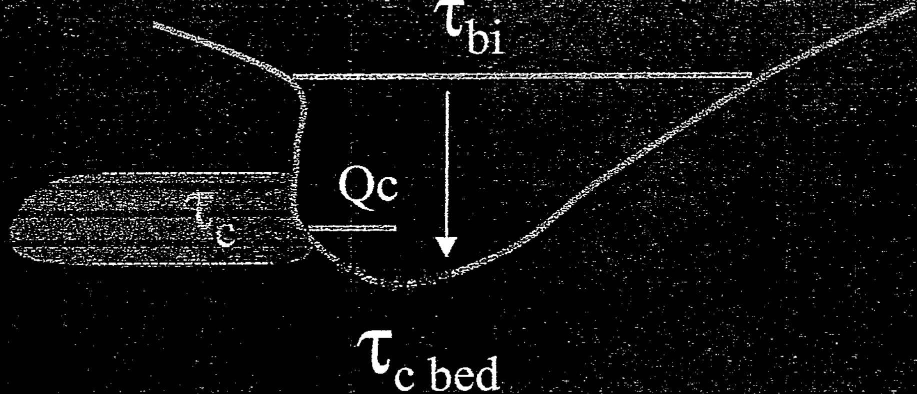
# Stability Assessment

- Requires a Baseline Condition
  - Pre-Urban
  - Existing
- Healthy Stable System
  - Balance among flow energy, sediment loads, and channel resilience exists naturally and should be maintained

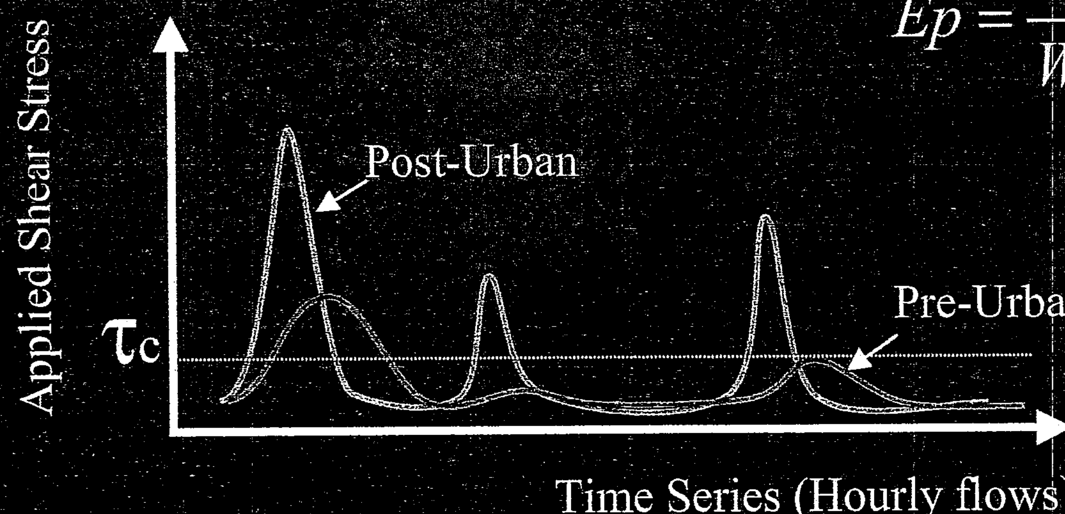
# Effective Work Index (*W*)

$$W = \sum_{i=1}^{n} \left(\tau_{bi} - \tau_c\right)^{1.5} \cdot V \cdot \Delta t$$

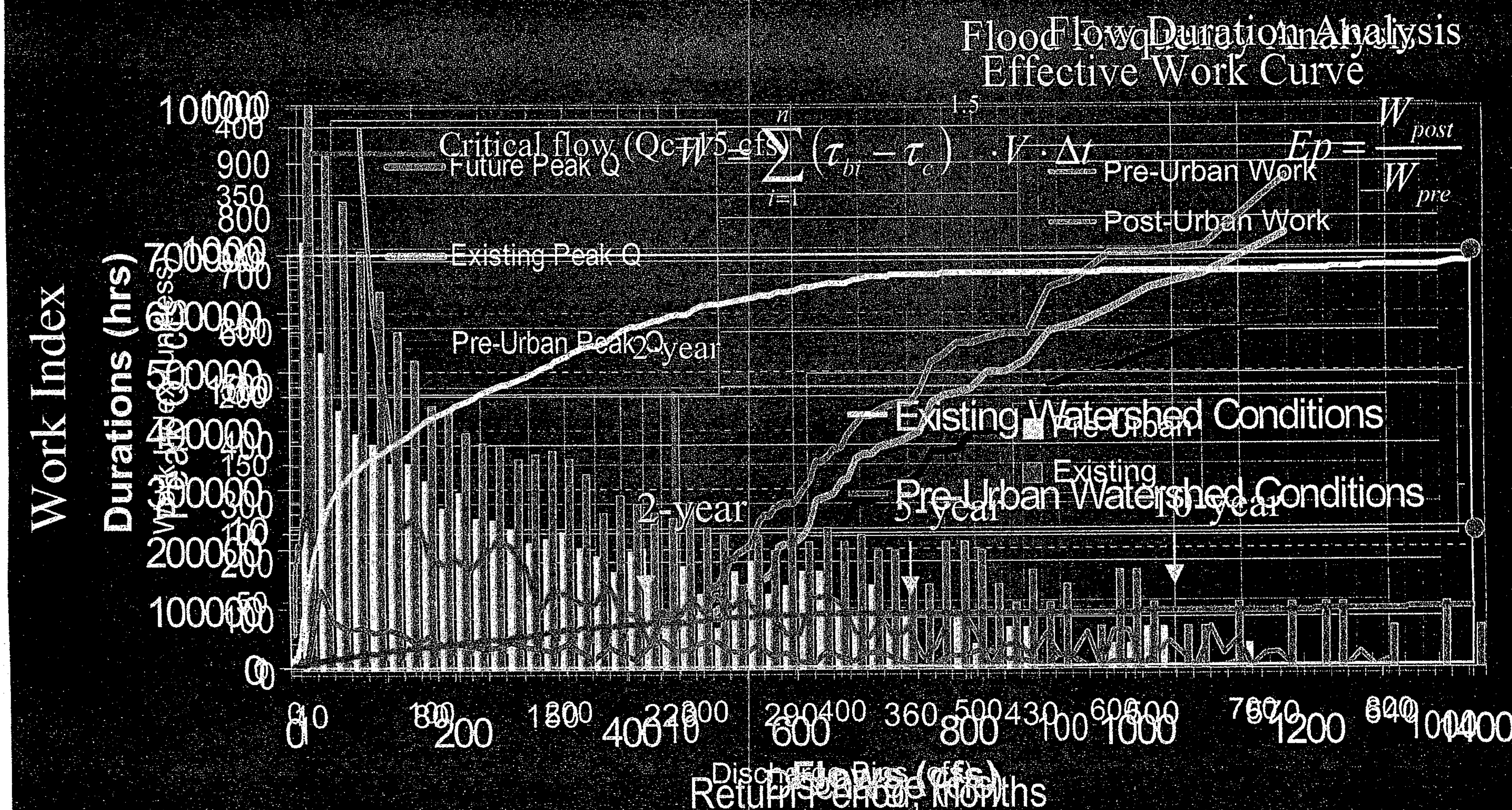



# Erosion Potential (*Ep*)

$$Ep = \frac{W_{post}}{W_{pre}}$$



# Analysis of Frequency Distributions

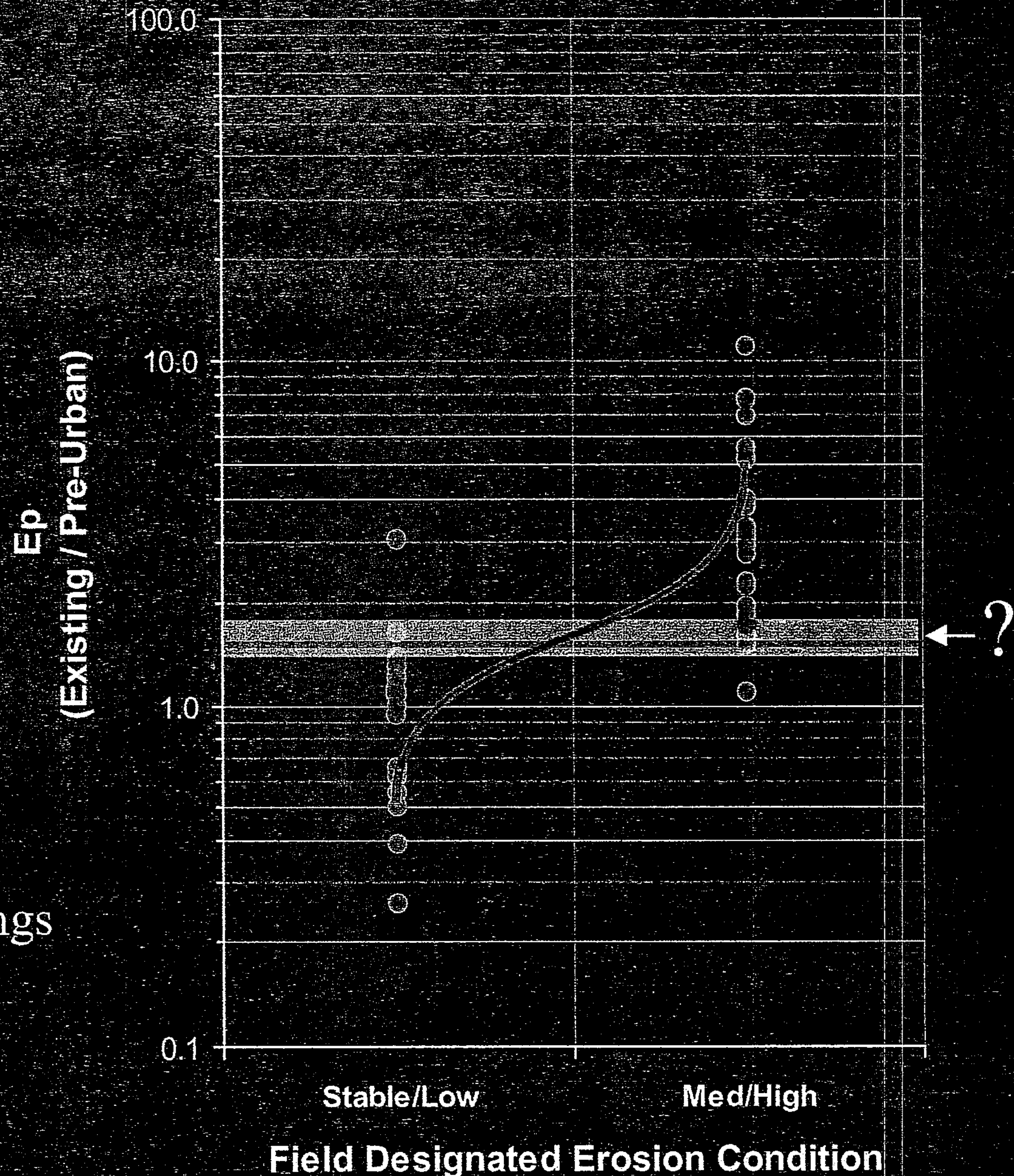


# Erosion Potential Chart

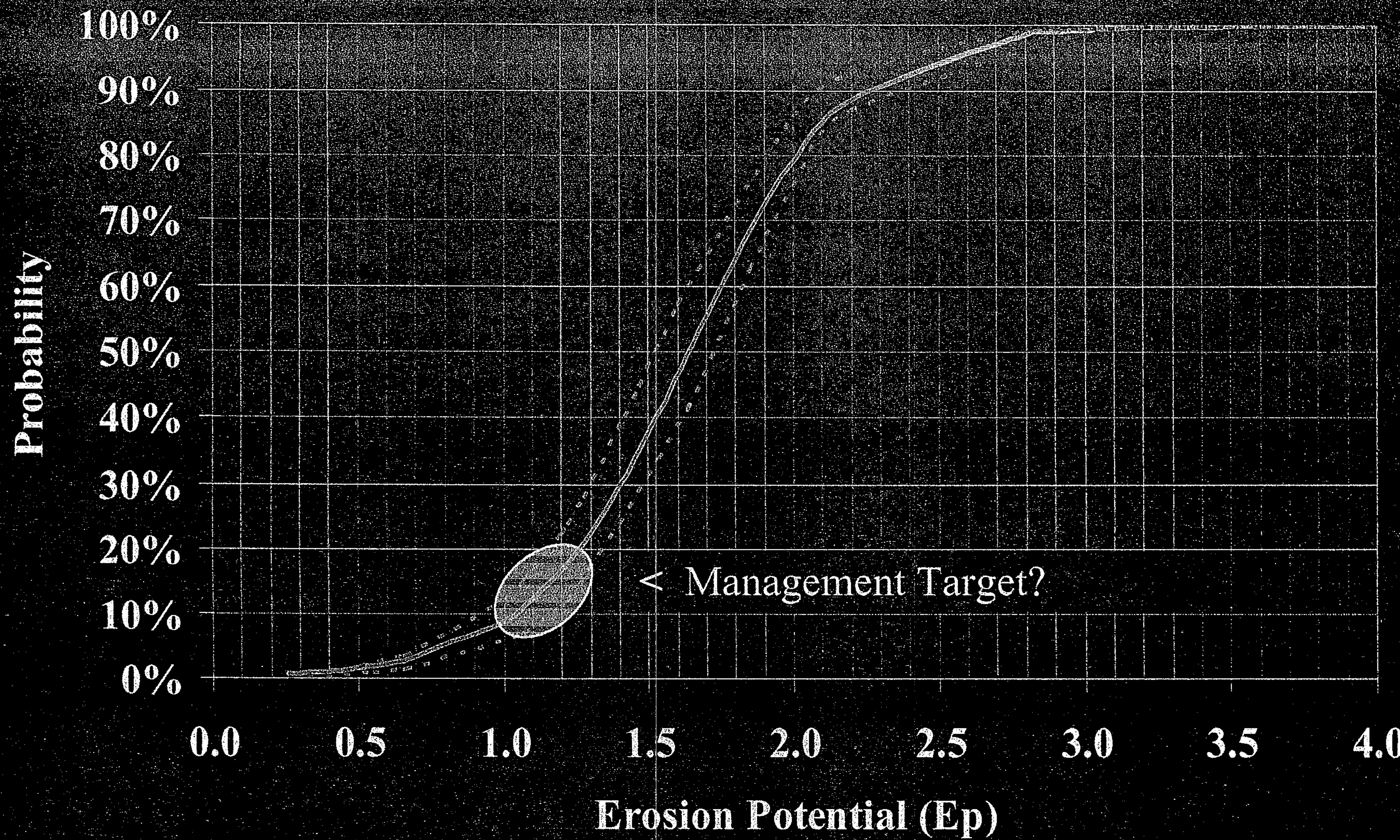
49 Cross Sections

- Thompson Creek
- Ross Creek
- San Tomas Creek
- Laurel Creek / Soda Springs

$$Ep = \frac{W_{post}}{W_{pre}}$$



# Risk of Channel Instability



# Hydromodification Management

- Maintain the baseline sediment transport capacity
- *Ep* = 1.2 for tests performed (*Risk* = 16%)

- Implementation
  - How do we translate the goal into on-site developer management strategies?

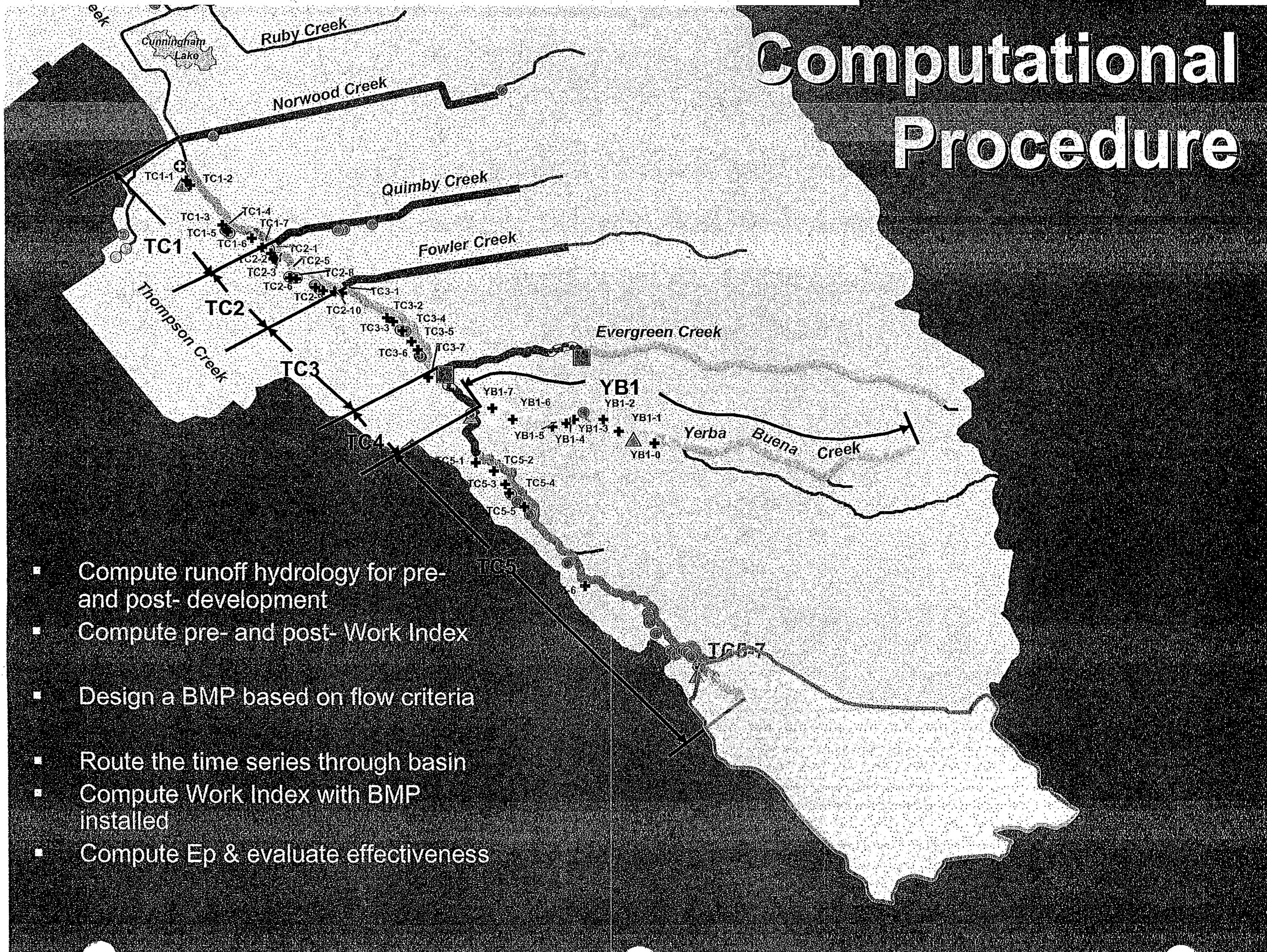
# Potential Control Measures

- Volume Controls
  - Site design (LID)
  - On-Site BMPs
- Flow Controls
  - On-site and regional
- Stream Modifications
  - Channel slope & geometry
  - Stream bed and bank materials

# Flow Control Measures Tested

- Peak flow control
  - 2-yr and 10-yr and 50-yr
  - 2-yr, disch @ ½ 2-yr peak
  - 2-yr, disch @ $^1/_{10}$ 2-yr peak (Local Qc)
- Hydrograph matching (volume & shape)
  - 2-yr, 10-yr, 50-yr
- Flow duration control

# Computational Procedure




- Compute runoff hydrology for pre- and post- development
- Compute pre- and post- Work Index
- Design a BMP based on flow criteria
- Route the time series through basin
- Compute Work Index with BMP installed
- Compute Ep & evaluate effectiveness

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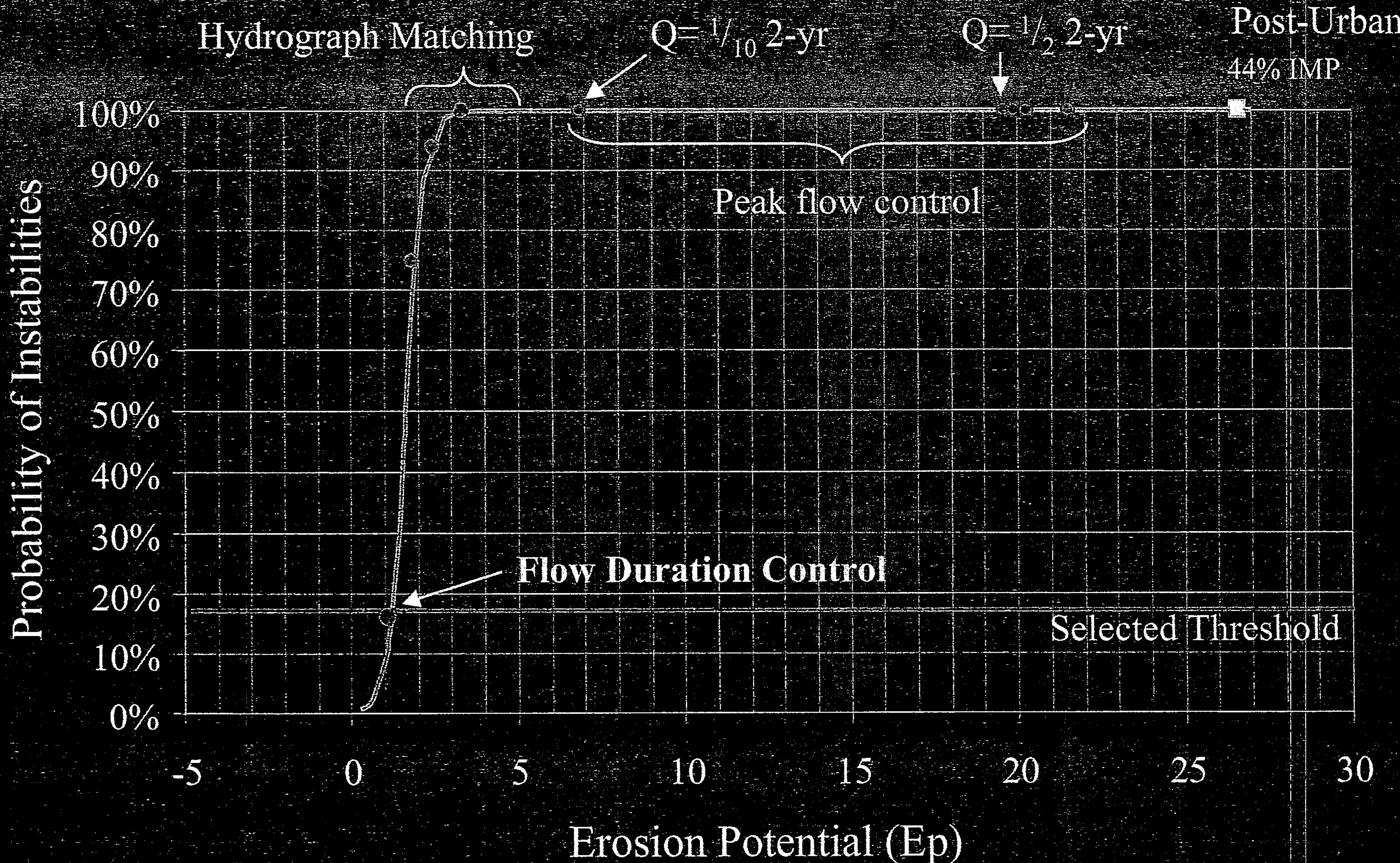
# Flow Control Effectiveness

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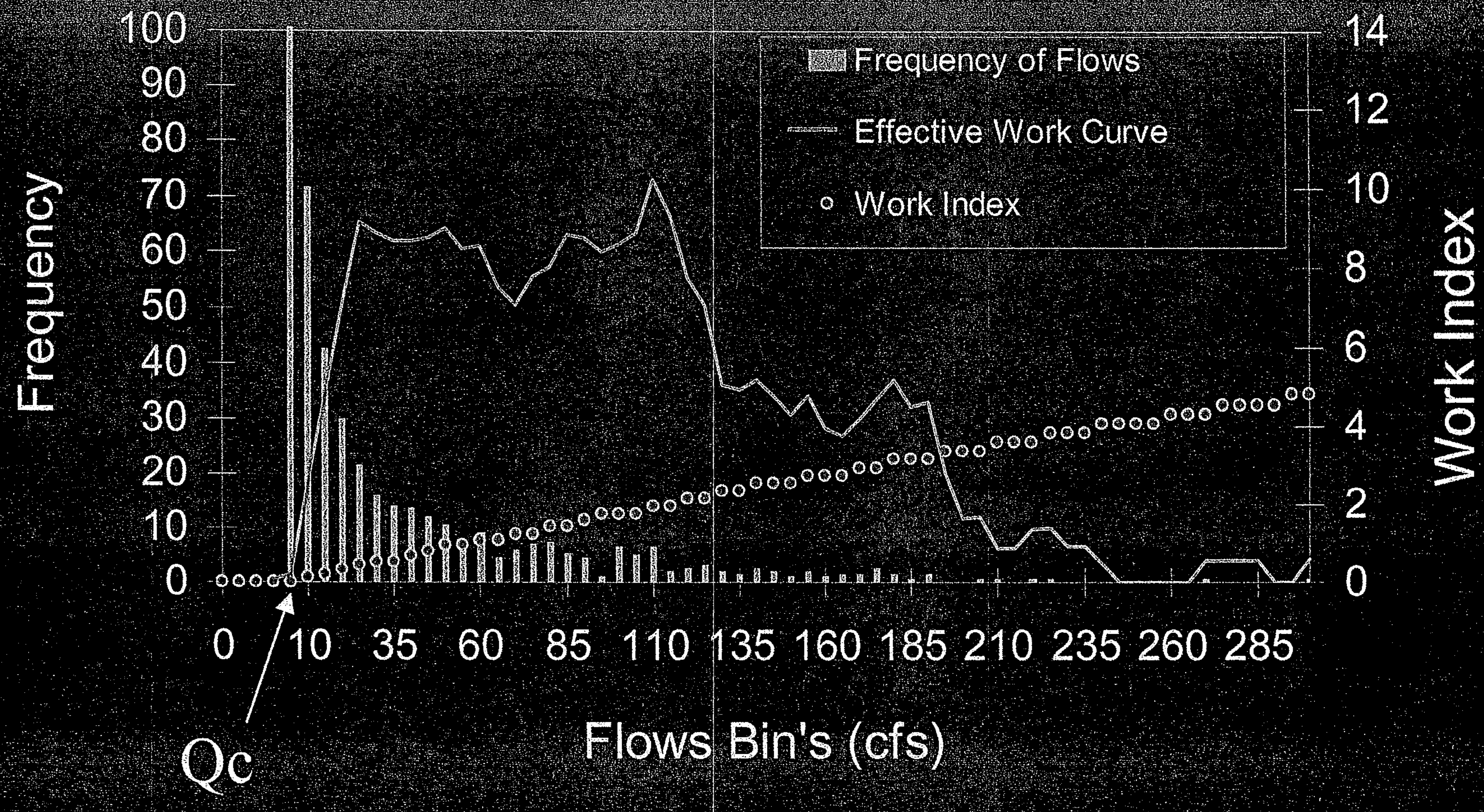
# Basis for Flow Duration Control

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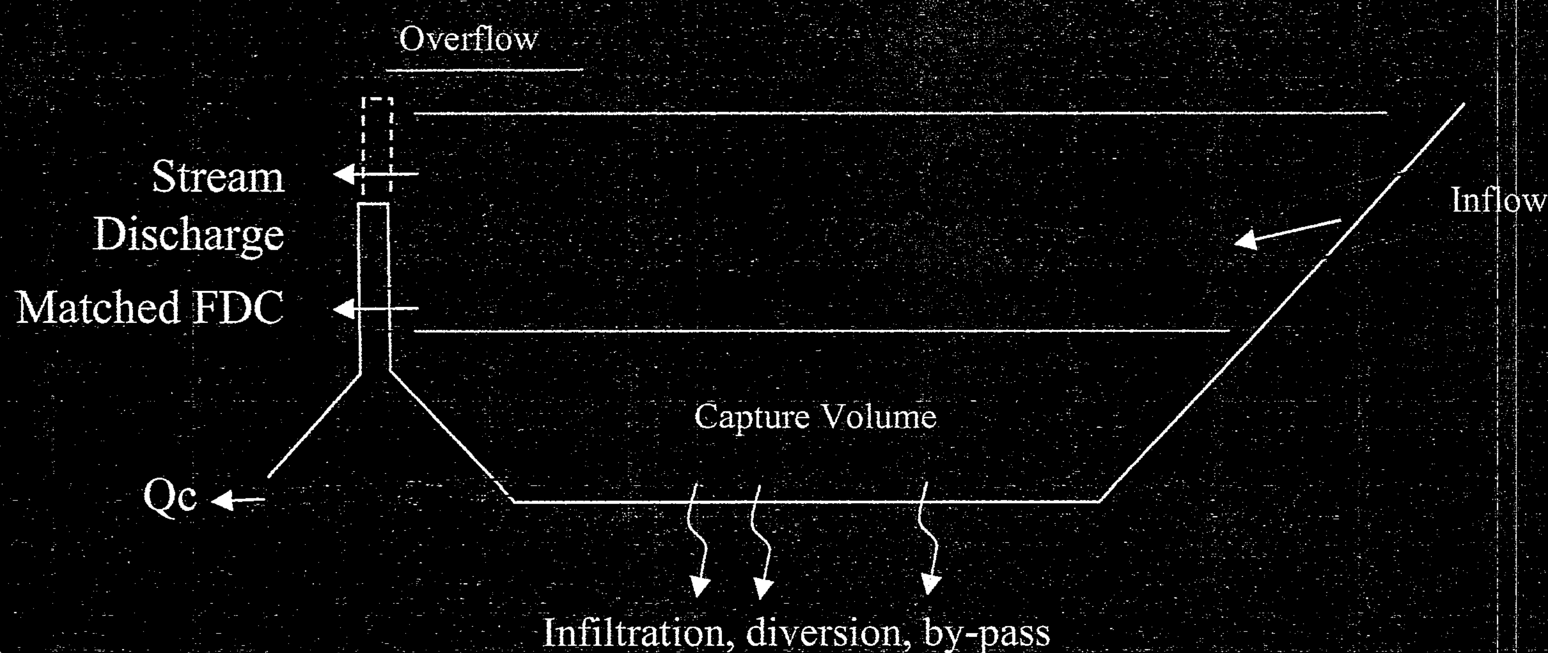
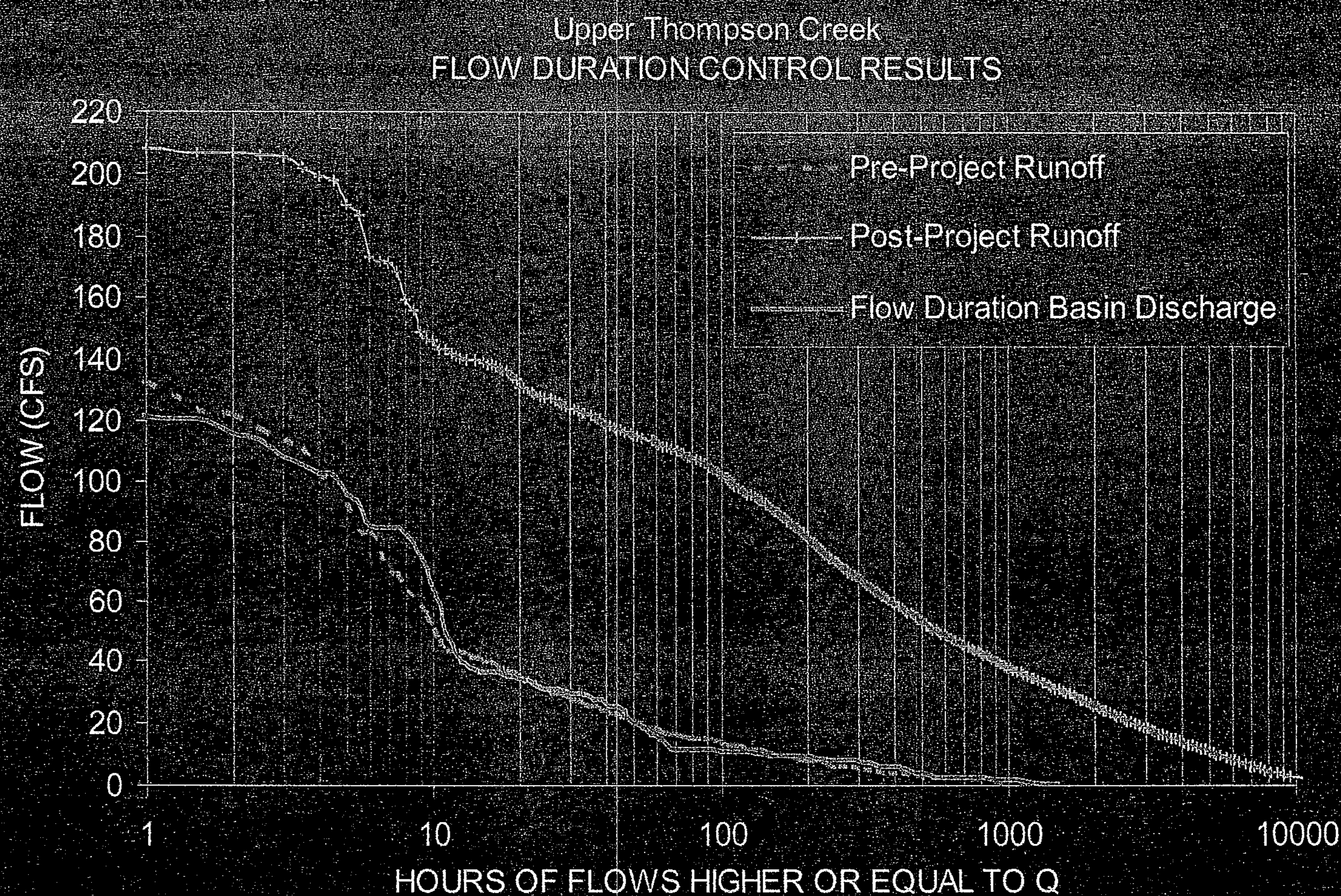
# Flow Duration Control
## Design Concept

- **Retain** increase in runoff volume
- Qc = 10% of the 2-year peak flow
- Match the discharge frequency distribution



# Flow Duration Curves



# Example FDC Basin Results

Results from Santa Clara and Alameda County Programs

| Feature | Range of Results | Comments |
|---|---|---|
| Basin Volume (ac-ft) | - | Varies with change in runoff volume |
| Basin Area (% DCIA) | 3 to 6<br>11 | Clay soils (0.1 to 0.2 in/hr)<br>Sandy soils (0.5 to 1.0 in/hr) |
| Basin Depth (ft) | 2 to 6 | Multiuse, safety issues |
| Drain Time (days) | 3 to 5<br>(3 days 80% to 90% of the time) | Santa Clara County Vector Control will allow up to 5 days |
| Qc (cfs) | - | Defined as 10% of the 2-year pre-project peak flow |
| Infiltration Rates | 0.1 to 1.0 | Dependent on local soils |

# Summary

- Reliable predictor of channel stability
- Links local watershed and development characteristics with geomorphic processes
- Incorporates a *risk* based approach for making management decisions
- FDC comes closest to maintaining the baseline sediment transport capacity

Thank You

Questions

# Development of a Hydromodification Management Plan for the Santa Clara Valley – Part 1: Assessment of Hydromodification Impacts and Control Measure Effectiveness

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## INTRODUCTION

It is well documented that urbanization modifies the natural watershed and stream hydrologic and geomorphic processes by introducing impervious surfaces and drainage infrastructure into a watershed (Bledsoe & Watson, 2001; Booth, 1990; Hollis, 1975; Hammer, 1972). Hydromodification has been defined as increases in surface runoff volume, frequency and duration resulting from development. Hydromodification intensifies sediment transport and often leads to stream channel enlargement and loss of habitat and associated riparian species (Bledsoe & Watson, 2001; Booth, 1990; MacRae, 1992).

The California Regional Water Quality Control Board (RWQCB) San Francisco Bay Region, under the National Pollutant Discharge Elimination System permit program for stormwater, is requiring dischargers to address the impacts from hydromodification. The Santa Clara Valley Urban Runoff Pollution Prevention Program (SCVURPPP) is subject to the new permit requirements, which included the development of a Hydromodification Management Plan (HMP). This paper summarizes the technical study supporting the development of the HMP.

To evaluate the effectiveness of the flow control strategies, a measure of the change in the amount of work done moving sediment and eroding stream banks in the receiving stream is compared between pre- and post-development conditions (MacRae 1996, SCVURPPP 2004). One important step was to determine a threshold, or level of change, that if exceeded results in an unacceptable level of *risk* in causing stream channel degradation. Studies conducted for the SCVURPPP as well as works published by MacRae (1996) have suggested that increases in the capacity to move sediment (or otherwise erode banks) of 20% above a pre-urban baseline condition is enough to initiate channel adjustment. In this paper, effectiveness is evaluated by how close flow controls maintain the pre-urban capacity.

## STUDY APPROACH

The studies conducted for Santa Clara involved the Thompson Creek, Ross Creek and San Tomas Creek subwatersheds, San Jose, California. Thompson Creek and the Ross/San Tomas Creek pair represent two distinct environs in the Santa Clara Valley Basin. For simplicity, this paper focuses primarily on the Thompson Creek study area.

The HMP approach is subdivided into five primary elements: 1) problem area and reach characterization, 2) geomorphic assessment, 3) hydrologic modeling, 4) stability assessment, and 5) effectiveness evaluation of solutions. As an example, Figure 1 presents a map of the Thompson Creek study area and cross section locations where the analysis was performed.

Problem area and reach characterization describes features of the watershed and stream channels necessary to understand the nature and extent of the problem and to explain existing conditions. Historical aerial photography, soils and geologic maps, channel maintenance records, infrastructure data and historical surveys were used to distinguish between urbanizing impacts and impacts caused by past land use practices.

The geomorphic assessment describes the geologic and geomorphic characteristics of the stream network, the dominant physical processes that seem to be controlling stream attributes and erosion, and the extent and modes of failure for observed eroding channel banks and beds. Field crews recorded reach-wide observations on streambed and bank erosion, collected location specific data at 60 cross sections (between all three test watersheds), and then assigned each location a rank of *stable, low, medium or high* observed condition of erosion, or likelihood of erosion in the near future. Several factors affecting channel bank and bed stability were combined with the extent, age, and magnitude of existing erosion to designate an appropriate erosion ranking.

A hydrologic continuous simulation model of the pre-project, existing, and future (year 2020) land use conditions was developed using the U.S. Army Corps of Engineers' Hydrologic Engineering Center - Hydrologic Modeling System (HEC-HMS). The model was calibrated using two years of measured flow data. The calibrated model was run using 50 years of rainfall record and produced a time series of hourly stream flows to analyze changes flow duration, runoff volume, and frequency between land use scenarios. The soil moisture accounting module was used to incorporate the affects of antecedent conditions.

The stability assessment is based on the premise that a balance among flow energy, sediment loads, and channel resilience exists naturally and should be maintained in order for the stream network to remain stable (GeoSyntec, 2002; McRae, 1996). The hypothesis is that, over time, the stream channel slope and geometry co-evolved with vegetation, local physiography and climate to establish its pre-development dynamic equilibrium. To maintain stream channel stability, the management goal is to maintain the pre-development flow energy, sediment transport and erosion characteristics.

An *index* representing the *total effective work* done on the channel boundary was derived and used as a metric to predict the likelihood of channel adjustment given watershed and stream hydrologic and geomorphic variables. The index under urbanized conditions is compared to the index under pre-urban conditions expressed as a ratio (Ep).

The effective work index ($W$) is computed as the excess shear stress that exceeds a critical value for streambed mobility or bank material erosion integrated over time and represents the total work done on the channel boundary:

$$W = \sum_{i=1}^{n} \left(\tau_i - \tau_c\right)^{1.5} \cdot V \cdot \Delta t_i \qquad (1)$$

Where $\tau_c$ = critical shear stress that initiates bed mobility or erodes the weakest bank layer, $\tau_i$ = applied hydraulic shear stress, $\Delta t$ = duration of flows (in hours), and $n$ = length of flow record. The effective work index for presumed stable stream channels under pre-urban conditions is compared to stable and unstable channels under current urbanized conditions. The comparison, expressed as a ratio, is defined as the Erosion Potential (Ep) following McRae (1992, 1996).

$$Ep = \frac{W_{post}}{W_{pre}} \quad (2)$$

where:

$W_{post}$ = work index estimated for the post-urban condition
$W_{pre}$ = work index estimated for the pre-urban condition

A "threshold of adjustment" is considered that distinguishes between stable and unstable conditions. The Ep and the threshold of adjustment are used to set management criteria and evaluate the effectiveness of proposed solutions (McRae, 1993).

## RESULTS

### GEOMORPHIC ASSESSMENT

The project team distinguished six hydrographic segments based on stream flows from large urban outfalls. Each segment has similar stream discharges and reflects important differences in channel flows.

*Channel Geometry and Slope*: Channel width and depth are extremely variable, with width generally differing by 4 to 5 times and depth by 2 to 3 times between cross sections. Segment 5 shows a rapid transition in channel geometry because changes from stable to unstable channel conditions are located within this segment. Channel slopes range by an order of magnitude (0.002 to 0.025 ft/ft) varying by cross-section throughout the reach.

*Bank Material*: Channel banks are not homogenous; instead they consist of multiple layers with different sediment characteristics that vary through the subwatershed. Thompson Creek is generally dominated by cohesive banks that are fairly resistant to erosion. Segments of the creek have exposed hardpan in various locations. Layers of moderately to well-sorted sands and gravels with some silt and clay often represented the weakest portion of the bank. Widespread undercutting often occurred at the weaker alluvial layer.

*Bed Material*: The channel bed is generally composed of gravel with some sand. The median grain size (D50) ranged from 3.2 to 10.2 millimeters. The median grain size falls within the very fine to medium size gravel class. The average values for critical shear stress and critical velocity are 0.14 lbs/sq-ft and 2.8 ft/sec, respectively.

*Erosion Classification*: Erosion rankings of *stable, low, medium,* or *high* were assigned to each cross-section. These rankings were qualitative in nature and no numerical standard was applied. Instead, all factors affecting bank and bed stability (slope, undercutting, bank slope, type and density of vegetation, obstructions) were combined with the observed extent, age, and magnitude of observed erosion to designate the rank. Cross-sections that received a rank of *high* were severely incised reach-wide or actively incising with eroding banks, either through processes of undercutting, shearing and/or slumping. Channel banks were generally vertical and bare with vegetation stabilizing only the tops of banks. Eleven of the thirty-seven cross-sections were assigned *high*. Cross-sections designated as *low* had banks that were not eroded or eroded but now stable. *Low* ranking cross-sections generally had gentler slopes and denser vegetation, and sometimes located behind grade control structures where the bed had aggraded. Cross-sections ranked as medium had characteristics in between those described for *high* and *low*. Thirteen of thirty-seven cross-sections were designated as *medium* and thirteen designated as either *low* or *low* to *medium*. A rank of *stable* was assigned to three upstream sections.

## STABILITY ASSESSMENT

*Erosion Potential (Ep)*: Figure 2 presents an Erosion Potential Chart with Ep plotted for each section sub-divided by the field designated erosion classification using all three test watersheds. All total, 45 cross sections collected between three test watersheds were used in the analysis. There is a good correlation between the observed erosion classification and the magnitude of the computed Ep. An Ep ratio of 2 means that the post-urban runoff condition exerts 2 times more total work on the channel boundary then under the pre-urban condition.

One of the objectives was to identify a *threshold* that could be used to define management strategies and discharge limitations. Figure 3 presents a probability curve using a Logistic Regression technique on the data presented in Figure 2. This technique relates the probability of having unstable channel conditions to the computed Ep (Bledsoe and Watson, 2001b). For example, given a computed Ep of 2, the likelihood of having unstable conditions is about 80 percent. The probability curve can also be used to select an Ep threshold by specifying a level of acceptable "risk" (i.e., probability that a stream channel is not stable). For example, to accept a 15% "risk", the Ep threshold would be 1.2. In this paper, flow controls are considered effective if they are able to maintain the Ep below the threshold of 1.2.

## MANAGEMENT STRATEGIES

Stormwater management strategies that were considered include pre- and post- peak flow control, volume matching, hydrograph matching, flow duration matching, and managing effective work through the erosion potential (Ep). Various combinations of BMPs can be used including on-site or project based controls, larger scale regional controls, and in-stream controls that modify the stream to accept the changed watershed hydrology. Results to date indicate that flow duration matching is a protective management strategy that can apply to on-site or project based controls which has the benefit of not requiring additional information on in-stream hydrology and stability. Ep control is more applicable to watershed wide master planning involving regional and in-stream controls and possibly for very large developments.

To evaluate various flow control strategies, the post-development runoff time series was routed through flow control basins with varying design strategies (discussed below). The resulting discharge time series was then routed through a selected cross section and the cumulative effective work and erosion potential computed. The resulting Index was then compared to the pre-development value to evaluate the effectiveness at maintaining the pre-development effective work, or sediment transport capacity. This approach is similar to that used by McCuen et al. (1988), MacRae (1996), and Rohrer et al. (2004). Three separate channel conditions were evaluated varying slope and bed material size so that we could test effectiveness under a range of conditions. The actual channel condition has a slope of 0.013 and a D50 of 4mm (Test 1). Slope was reduced to 0.004 (Test 2) and the D50 was increased to 12mm in the other case (Test 3; critical shear stress increased to 0.42lbs/sq-ft).

*Flow Control Strategies Tested*

Strategies range from peak flow control, hydrograph matching for individual storm events, and flow duration control. Table 1 summarizes the tested strategies.

**Table 1. Summary of Flow Control Strategies Tested**

| | |
|---|---|
| ❖ **Peak Flow Matching**<br>➢ 2-Year Peak Flow<br>➢ 2, 10, & 50-Year Peak Flow<br>➢ 2-Year peak discharged at ½ its rate, plus 10-Year Peak Flow<br>➢ 2-Year peak discharged at <Qc ($^{1}/_{10}$), plus the 10 Peak Flow | ❖ **Hydrograph Matching**<br>(includes peak, volume and event duration)<br>➢ 2-Year Discrete Event<br>➢ 10-Year Discrete Event<br>➢ 50-Year Discrete Event<br>❖ **Flow Duration Matching**<br>➢ Flow Duration Control (involves volume control) |

Peak Flow Matching

Management facilities are often designed to maintain peak flow rates at their pre-development levels to prevent increases in the frequency of flooding. It has been common for stormwater managers to specify control of the 2-year peak flow to protect streams from excessive erosion and enlargement with the premise that this event "controls" the shape of the stream. It has been demonstrated that 2-year peak flow control strategies are not adequate (MacRae, 1996) because this approach does not consider increases in the length of time (duration) that flows persist at this rate. Four peak flow control scenarios were tested in this study (Table 1). These include: maintain the 2-year peak flow rate; maintain the 2-, 10-, and 50-year peak flow rates; capture the 2-year event and discharge it at *one-half* its pre-development rate plus maintain the 10-year peak flow; and capture the 2-year event and discharge it under the critical flow for bed mobility (i.e., for Santa Clara streams Qc ≅ *one-tenth* its pre-development 2-year peak flow rate) plus maintain the 10-peak flow rate.

Hydrograph Matching

Hydrograph matching maintains the pre-development discrete event peak flow, runoff volume, and storm event duration (i.e., hydrograph shape). This is an important step because the increase in runoff volume from impervious areas is a major factor contributing to the impacts of hydromodification. Separate flow controls were designed for the 2-year, 10-year, and 50-year hydrographs. These flow-control BMPs capture and *retain* the difference in runoff volume between the pre- and post-development hydrographs. The captured volume is either infiltrated or released to the stream at a rate less than the critical flow for bed mobility.

Flow Duration Control:

Stream erosion/deposition and sediment transport processes are functions of the long-term cumulative effects of geomorphically significant flows. Maintaining the long-term cumulative duration of geomorphically significant flows maintains the capacity to transport sediment and promotes long-term stability.. Flow duration control appears to have first been proposed in the literature by Derek Booth (1993), University of Washington. Flow duration control maintains the pre-development frequency distribution of hourly runoff as well as the total runoff volume. The captured volume must be infiltrated and/or released at less than the critical flow for bed mobility. The flow duration method is essentially an analysis of distributions of all flows as opposed to using a single design event(s) and assuming that this event correctly captures all the relevant characteristics of hydromodification. A distribution of hourly rainfall is transformed to a distribution of hourly runoff using the hydrologic model. The distribution of runoff is then analyzed for long-term cumulative flow duration. This approach incorporates the full probability distribution of storms; including 2-year through 50-year storms, frequent erosive flows less than 2-year storms, droughts and heavy winters, antecedent conditions, and back-to-back storms.

## Results & Discussion

Table 2 lists the computed erosion potentials for pre- and post-development using the upper portion of Thompson Creek as a test case with the various flow controls. The post-developed condition is predicted to increase the long-term cumulative work by more than 20 times depending on channel conditions.

Peak Flow Matching

Peak flow control strategies have Ep ratios ranging from 4 to 20 with risks of instability of 100% and would not be considered effective at protecting beneficial uses of stream systems. Capturing the 2-year event and releasing it at a fraction of its pre-development peak improves the results, but still results in a 100% likelihood of causing stream channel instabilities (Figure 3). These strategies detain storm runoff and shifts higher flows to lower flows where the majority of the sediment load is transported. Tests 2 and 3 with higher critical flow rates illustrate the benefits of having higher critical flows (Qc) for bed mobility. MacRae (1996) found that peak flow controls can even make the problem worse than doing nothing at all, because high flows are shifted to lower flows where a large majority of the total sediment load is transported. During high flows, some portion of the total flow is not contributing to work moving sediment in the main channel, but when shifted to low flows it adds to the total work done transporting sediment; e.g., when normal floodplain waters are held in a basin and discharge at rates at or less than bankfull.

Hydrograph Matching

The single hydrograph matching approach performs much better than peak flow controls because of the reduction in total discharge volume, however, most still have an unacceptable *risks* of stream channel instabilities. The 50-year basin retains a larger amount of runoff than the 10-year, which retains more than the 2-year basin. The 50-year basin Ep ranges from 1.9 to 2.6 times the pre-urban level, which is predicted to have a risk of instability ranging from 70% to 98%. The 10-year basin has a risk of instability ranging from 92% to 100%. Retaining the increase in runoff volume caused by development on-site could potentially slow the rate of channel adjustment. Unfortunately, matching single event hydrographs must be considered ineffective, and using this approach on a large scale would not likely protect the beneficial uses of streams from the effects of hydromodification.

***Flow Duration Matching***

Flow duration control maintains the pre-developed (or pre-project) distribution of in-stream flows above the critical flow for bed mobility and as a result maintains the pre-developed capacity to transport sediment, or contribution to the erosion/deposition processes. This is reflected in Table 2, where the computed Ep ranges from 0.8 to 1.1. The risk of instability is 12% - less than the selected threshold of adjustment (Ep=1.2, Figure 3). Flow duration control is also matching the pre-developed runoff volume for the full range of flows. For example, the pre-developed duration of flow between 5 to 10 cfs is maintained and thus the volume of runoff with this flow rate is also maintained. Flow duration control maintains the distribution of flows for selected ranges; e.g., 0 to 5 cfs, 5 to 10 cfs, 10 to 20 cfs, etc. to maximum flow. In a sense, flow duration control manages the distribution of erosive flows.

**Table 2 – Resulting Erosion Potential (Ep) for Tests Conducted**

| No. | Flow Control Strategy | Test 1<br>Qc = 2 cfs<br>Slope = 0.013<br>D50 = 4mm | Test 2<br>Qc = 12 cfs<br>Slope = 0.004<br>D50 = 4mm | Test 3<br>Qc = 17 cfs<br>Slope = 0.013<br>D50 = 12mm |
|---|---|---|---|---|
| **Assumed Future** (44% IMP) | | 27 | 26 | 24 |
| **Peak Flow Controls** (no volume control) | | | | |
| 1 | 2-Year Peak Flow | 22 | 5.4 | 5.2 |
| 2 | 2-, 10-, & 50-Year Peak Flow | 20 | 6.1 | 5.1 |
| 3 | (1/2) 2-Yr + 10-Year Peak | 20 | 3.6 | 3.6 |
| 4 | (1/10) 2-Yr +10-Year Peak | 6.9 | 3.9 | 4.1 |
| **Hydrograph Matching** (includes peak flow, volume and duration) | | | | |
| 5 | 2-Year Discrete Event | 3.3 | 4.0 | 4.1 |
| 6 | 10-Year Discrete Event | 2.4 | 2.8 | 3.1 |
| 7 | 50-Year Discrete Event | 1.9 | 2.3 | 2.6 |
| **Flow Duration Matching** | | | | |
| 8 | Flow Duration Control | **1.1** | **0.8** | **0.9** |

It may be tempting to select a discrete method noting that a significant improvement can be made when volume control is applied. The 2-year hydrograph matching reduced the Ep from 27 to 3.3, a nine fold reduction. Unfortunately, this big improvement will not meet our objective of protecting the stream system from excessive erosion and its related responses.

To put things in perspective, Figure 4 presents the probability curve with its X-Axis rescaled to show the range of Ep computed by the authors for Test 1. This figure illustrates how much change can occur when a watershed is developed and moreover the level of control that must be implemented to be protective. A management objective defined as maintaining the in-stream erosion potential within the selected limit requires a very tight control over urban runoff relative to the magnitude of change that only FDC seems to accomplish.

## CONCLUSIONS

1. Hydromodification and associated channel enlargement are best addressed as the long-term cumulative process of all erosive flows opposed to using discrete event methods.
2. Urbanization increased the duration and erosion potential of small to moderate size flows more than those for larger flows.
3. The effective work index (*W*) distinguishes between stable reaches (pre-urban, stable/low existing conditions), and unstable reaches (medium/high existing conditions).
4. The Ep Chart and Logistic Regression show a strong indication of a *threshold of adjustment* and express the likelihood or "risk" of channel instability from hydromodification.
5. The Ep methodology is best used to address cumulative watershed scale modifications in land use and hydrology during master planning or for larger scale development projects.
6. Ep can be used to evaluate the effectiveness of hydromodification management strategies, including on-site, regional, in-stream projects, or a mix of strategies.
7. Peak flow control strategies are not effective. Peak flow methods neglect the cumulative effects over time and potentially shifts flows from a non-sediment transport regime to a transport regime; e.g., moving floodplain flows into the main channel.
8. Hydrograph matching strategies can reduce the magnitude of hydromodification effects due to the added benefits of volume control, but are not likely to be effective.
9. Flow duration control reduces the erosion potential below our selected threshold of adjustment (Ep=1.2). Flow duration control is a form of volume control, and as such requires on-site project based volume reduction strategies, such as infiltration.
10. The critical flow for bed mobility (Qc) is an important factor in achieving effective management. Flows greater than Qc should be considered when addressing the effects of hydromodification. The increase in runoff volume resulting from impervious surfaces can be detained and discharged under Qc.
11. Flow duration control can be applied at the end-of-pipe or in smaller units spread throughout a development. Flow duration analysis can be used to compute the total storage volume and land area requirements for a single large facility or for multiple smaller devices, such as Low Impact Development.

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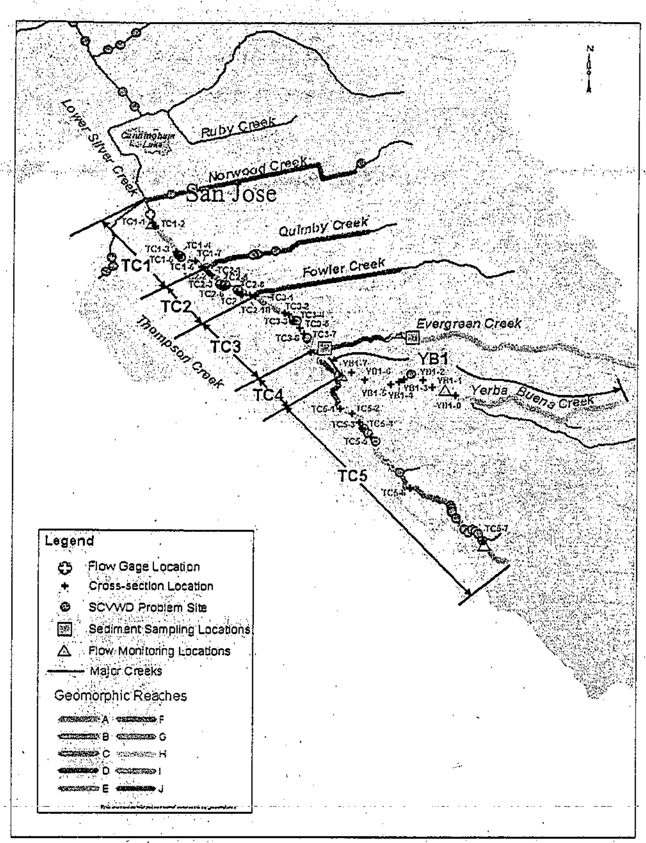


**Figure 1. Example Watershed Study Characteristics for Thompson Creek**

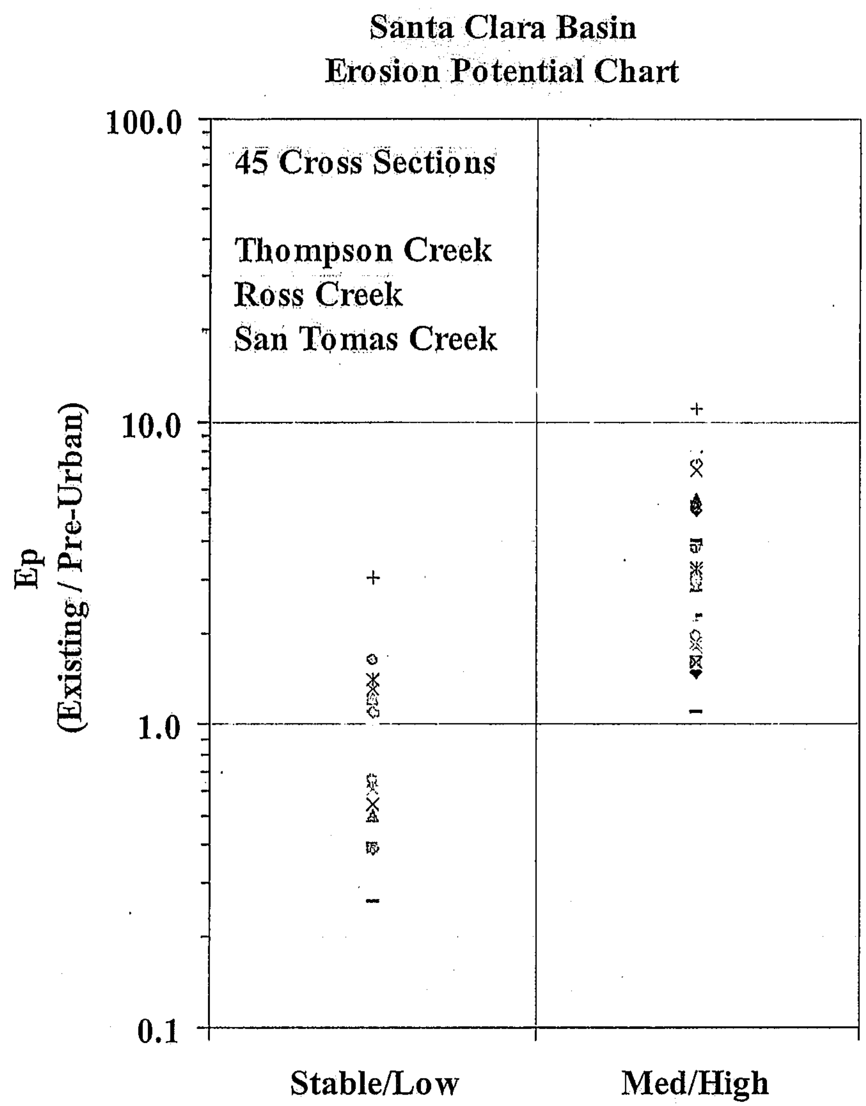


**Figure 2. Erosion Potential Chart illustrating Ep for each cross-section based on erosion classification (low, medium and high)**

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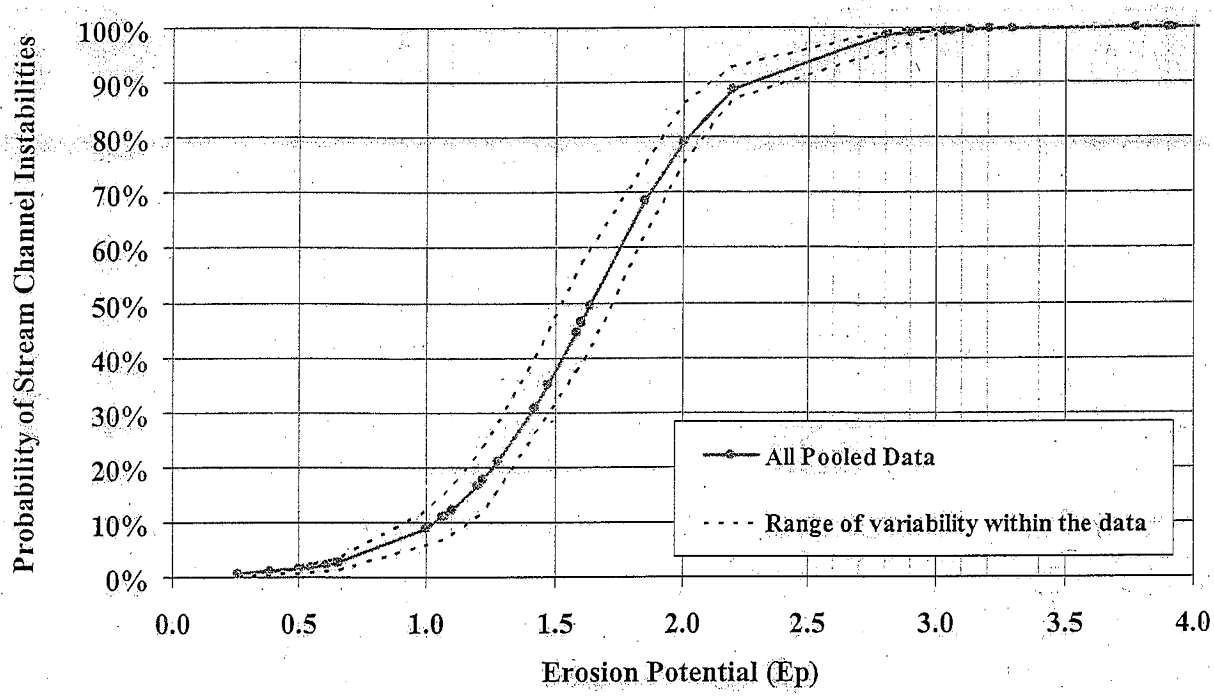



Figure 3 – Probability of Stream Channel Instability for the Santa Clara Valley Basin

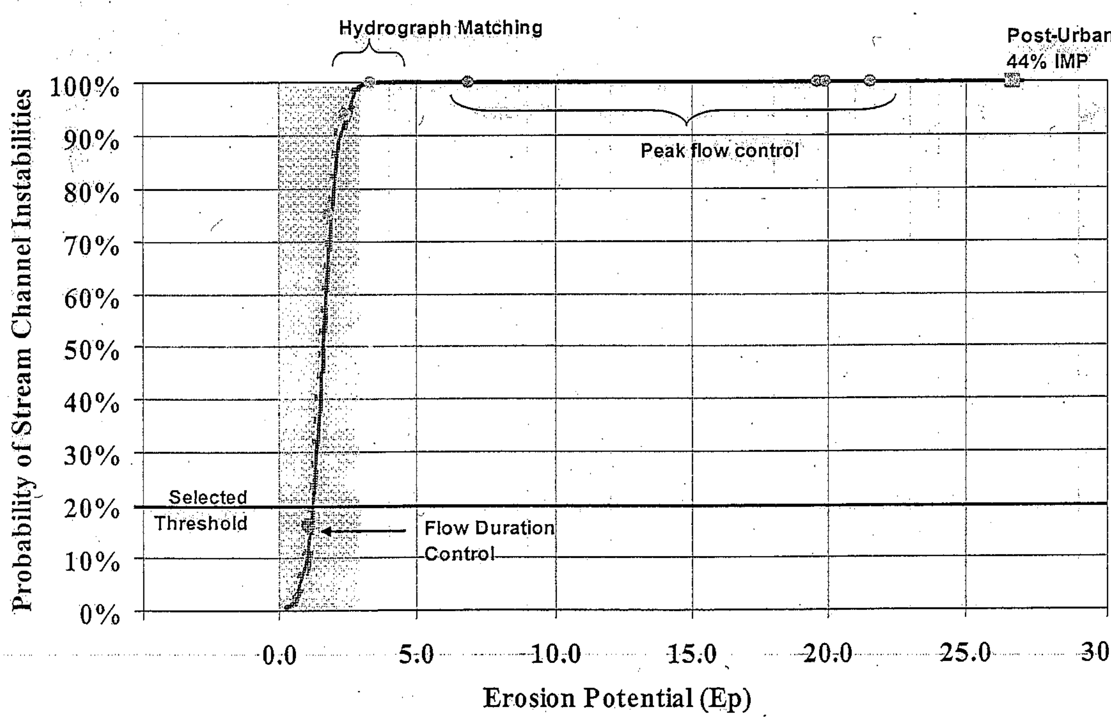



Figure 4 –Ep Values Computed for the Tested Flow Control Measures

**Comments by Brian Bledsoe, Department of Civil Engineering, Colorado State University on**

*Hydromodification Management Plan Report (incl. Appendices)* by the Santa Clara Valley Urban Runoff Pollution Prevention Program, Public Review Draft June 2004

and

*Technical Requirements and Geographic Areas for Hydromodification Management in Santa Clara Valley Basin* by GeoSyntec Consultants and others, Final Report June 2004

***General Comments***

I commend the project participants for developing a fundamentally solid strategy for managing hydromodification in the Santa Clara Valley. The procedure has a strong physical basis and encompasses the most critical physical processes without becoming unnecessarily complex and cumbersome. The conceptual approach also reflects the best available science. Numerous studies examining the effects of urbanization on channel stability underscore the importance of controlling the small to moderate sized events (less than a 2-year return period) that tend to be most magnified by development. The procedure necessarily relies on continuous flow simulations to quantify the duration of erosive flows and cumulative geomorphic work exceeding the threshold for erosion of limiting boundary materials. Although some practicing engineers are reluctant to move beyond single-event / design storm approaches, continuous hydrologic simulation at the time scale of decades is essential for adequately managing hydromodification in urbanizing watersheds. Combining a cumulative measure of geomorphic work and logistic analysis to link erosion potential with measured channel responses is innovative and entirely appropriate for quantifying the risk of channel instability.

Although the procedure is underpinned by sound hydrologic and geomorphic understanding, there are still are number of details that will have to be worked out to ensure physically reasonable and consistent parameterization of the models used to characterize flow changes. Model parameterization still leaves substantial latitude in characterizing pre- and post-development conditions. For example, if I hypothetically set out to minimize the flow controls required on a new project, what would prevent me from:

- Choosing unrealistically low infiltration rates for the pre-project condition?
- Choosing high infiltration rates for the post project condition despite the reality that heavy equipment compacted much of the site?
- Selecting unrepresentative stream sampling locations with relatively coarse materials and resistant boundaries?
- Picking the highest available estimate for critical shear stress for the limiting boundary material when better estimates are available in the literature?
- Placing stone grade control structures in the channel without careful analysis and claiming that I had mitigated the potential impacts to the extent practicable?

Conversely, input parameter uncertainty could also result in excessive "over control" and unwarranted costs to permit applicants. Therefore, it is critical that clear guidance be provided for parameterization in conducting HMP modeling studies. HEC-HMS, SWMM, and HSPF vary substantially in infiltration / soil storage algorithms and adequacy for modeling site-specific differences in development style and drainage infrastructure. How will consistency between new HMPs and the modeling techniques and inputs used to calibrate the risk criterion of Ep <1.2 be ensured? I currently don't see specific guidance that would prevent 'apples and oranges' comparisons. The SCS soil permeability values are notoriously inaccurate for developed lands. Results will also vary depending on how watersheds are discretized and the spatial resolution of distributed models. I strongly support the development of a standard regional model (akin to the King County, WA approach) to provide a consistent and transparent tool that constrains inputs to realistic values, and reflects the best available scientific information and latest calibration data. Moreover, geomorphic sampling must occur at a spatial density that results in representative inputs that reflect less resilient stream segments.

It is reasonable to provide options that include instream practices. But instream practices like grade control should be carefully designed in accordance with analytical stable channel design procedures and sediment transport modeling. For example, inappropriate design of grade control can store sediment and initiate headcutting in downstream reaches. If adequate standards for assessing the likely geomorphic impacts of proposed instream practices are not developed, these approaches could result in channel destabilization and degradation of designated uses.

It is important to acknowledge that the performance criteria may require adjustment and updating as more data and experiences are garnered. An important physical process that is not well represented in the approach is the potential for changes in sediment *supply*. Trapping of sediment by BMPs and the nature of development and its location relative to source areas could have important implications for channel stability and the degree of flow control required. Simply considering Lane's balance or Schumm's qualitative response tells us that perfectly matching the pre-development flow regime does not necessarily ensure channel stability, especially in "live bed," capacity-limited channels. Perhaps one of the most compelling arguments for selecting a very low risk of instability is the fact that the calibration procedure used to develop the logistic curve may not adequately account for sediment "starvation" due to BMP trapping and imperviousness. How much monitoring of channel stability will occur after an HMP is implemented? Additional channel habitat and stability data are critical for assessing the adequacy of protection provided by the management criteria and for improving the robustness of the logistic model through cross-validation.

There is a general inconsistency in the language used to describe the flow attributes of concern. "Peak flows", "duration", "rates", and "timing" are all interspersed in the document without clearly defining what is meant. Perhaps the aim could be described as controlling the overall "erosion potential" or "flow effectiveness" and the terminology could be clarified early in the document by describing how the controls relate to the various aspects of flow regime. I suggest using consistent wording throughout after defining specifically what is meant by erosion potential or some other term that encompasses the effects of altered flow peaks, durations, and rates.

The statistical analyses are appropriate. Although the risk model is based on a valuable set of geomorphic data, I recommend additional field verification and cross-validation of the logistic model over time. Of course, choosing a risk level involves politics and values. I suggest trying to help stakeholders understand that a 14% risk means that on average about one in seven stream segments will become 'unstable' and degraded, even if the controls are implemented per recommendations. Besides the costs of implementing the controls, such value judgments should also be based on consideration of larger-scale impacts potentially arising from increased downstream sediment delivery and migration of headcuts into upstream segments that were adequately protected, potential TMDL requirements, and loss of property due to bank failure. In other words, accepting some degree of instability could have geomorphic implications that extend well beyond a destabilization of a single reach of stream. This underscores the need for ongoing monitoring and analysis.

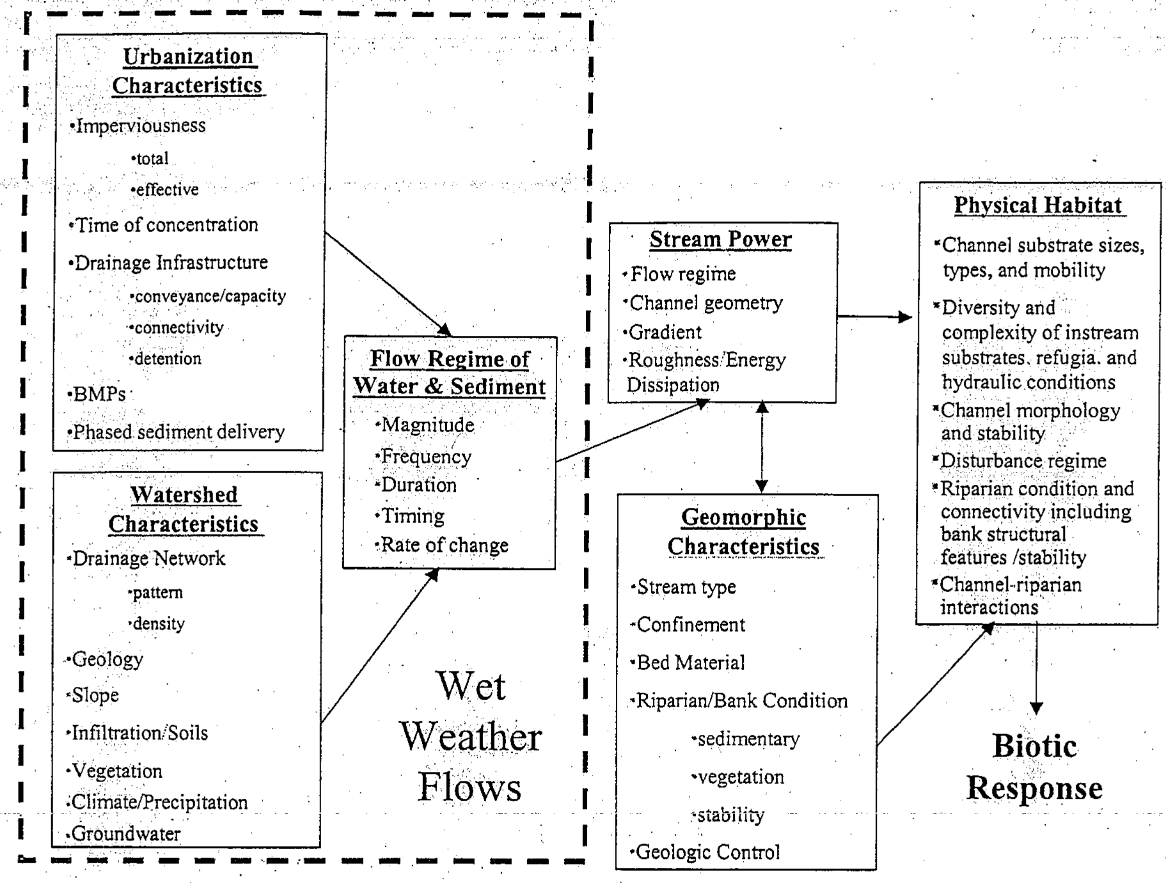
Achieving and Ep of 1.2 on a site-by-site basis is not equivalent to achieving a cumulative Ep of 1.2 in the overall system. It is analogous to the old Q2 'peak shaving' approach. Q2 peaks may be maintained site by site but synchronization of peaks can actually exacerbate flooding. The same principle applies here, despite the fact that durations are controlled. This suggests that watershed level planning could improve the likelihood of mitigating stream impacts.

It is tempting to say that the Ep analysis method is 'easy' because it only requires a representative grain size, cross-section, slope, and Manning's n value. But selecting representative values of these parameters in heterogeneous stream segments and drainage networks is not a trivial issue. Again, what sort of minimal spatial resolution is necessary? Should the modeling be targeted at relatively vulnerable reaches that could trigger larger scale responses?

I'm very glad to see the emphasis on operation and maintenance of HMP practices.

***Specific Comments***

After perusing Figure 2-1 again, it seems unnecessarily complicated, despite the complexity of the processes involved. It also seems to be missing important linkages between *sediment supply* and the surface runoff / soil type, land use w/BMP, vegetation type boxes. An oversimplification that Larry Roesner and I came up with and published in a WERF document is provided below (although this figure should more explicitly link geomorphic characteristics with sediment regime as well).




P. 3-8 The work index includes velocity to "accurately represent W in units of work." This is more of an academic comment but the statement is not entirely accurate because velocity and shear are not raised to the same exponent. It is not clear how the conversion factor works. If the exponent stays at 1.5, one could take velocity to the same power and then convert to unit bedload transport rate ala Bagnold who used specific stream power to the 1.5 power for his relationship. Yvonne Martin and Mike Church presented an

improved Bagnold equation of this form in a recent Earth Surface Processes and Landforms paper.

Pg. 3-10 How many flow bins are required? Can they be arithmetic or logarithmic? I suggest looking at Phil Soar and Colin Thorne's work for guidance on this issue.

Figure 3-6 Why are RC-1 and RC-2 located in the middle of the chart? What does the labeled arrow mean?

Pg. 3-17 Doesn't Qc potentially depend on bank erosion in addition to "bed movement?"

Pg. 3-18 The statement that the "watersheds are not significantly different to warrant…" seems to contradict statements at the top of next page and also has statistical connotations.

Pg. 3-19 The statement that "Ross Creek may be more resilient than Thompson Creek" seems tangential without further explanation. I agree that it is important to emphasize that the Ep approach is referenced to watershed-specific baseline conditions.

Pg. 4-4 The minimum duration controlled flow is set to 10% of the pre-project 2-year peak flow. Is the 2-year pre-project peak flow associated with peak flows occurring in a certain time increment (hourly, 15 min?) in the total flow series, partial duration series, or annual maximum series? If the answer is partial duration, how are the threshold and inter-event time defined?

Pg. 4-5 The circle points of varying shade on Figs. 4-1 and 4-2 are not adequately explained. Are 5-year peak flows labeled as 2-year peak flows in Fig. 4-2?

Pg. 4-12 What determines whether some combination of volume controls and instream controls meet objectives "to the maximum extent practicable"? It is good to give people options and room for creativity but this loophole seems to have the potential to undermine the objectives of the strategy. Could this be changed to say that the combination of practices must be demonstrated to provide protection equivalent to the duration/work controls or a variance be obtained? This is obviously a policy issue but it is also a scientific one in that it will be difficult, at best, to quantify what is "practicable" or equivalent.

Pg. 4-14 I hope tidally influenced areas are not exempt from water quality BMPs. Erosion of manmade conveyances can degrade designated uses of receiving tidal waters.

Pg. 4-23. The top diamond in the diagram refers to size criteria. Were these criteria described in the document? Do the size criteria refer to development size and/or stream size? How large does a channel have to be to require a HMP?

Pg. 5-7. Top of page- "mosquito production is reduces."

Pg. 5-15 SCS soil permeability values are notoriously inaccurate, especially in areas subject to compaction.

Pg. 6-8 What is a "reasonable time frame" for construction of instream controls?

References – the Western Washington document is not consistently cited in the text and is sometimes cited to as "King County."

Appendix B Pg. 34. The equation from Andrews (1983) is for armored gravel bed rivers and the D50 in the denominator is the D50 of the *subsurface* grain sizes below the coarse surface layer. Andrews and Nankervis (1995) presented new relationships of this type that are referenced to the *surface* D50. Beta in the surface referenced equations is typically between –0.9 and –1. I recommend using the best available science from mixed sand / gravel bed systems (e.g. studies by Peter Wilcock and Roger Kuhnle) to estimate critical shear stresses for bed material.

App. B, Pg. 56, Citation 5 change "Brain" to Brian

Appendix F. The discussion of logistic regression fails to mention one of the most useful and intuitive measures of logistic regression model performance: % correctly classified.

Pg. F-3. What precipitation record length is required? What flow record length is required? If a ~50 flow record is needed, will this be part of the HMP requirement? Will it be necessary to extend short precipitation records using correlations with other gages or stochastic modeling or simply repeat short records?

**Comments on by Thomas Dunne, University of California Santa Barbara on**

***Hydromodification Management Plan Report (incl. Appendices)***
**by the Santa Clara Valley Urban Runoff Pollution Prevention Program,**
**Public Review Draft June 2004**

**and**

***Technical Requirements and Geographic Areas for Hydromodification Management in Santa Clara Valley Basin***
**by GeoSyntec Consultants and others, Final Report June 2004**

The consultants have developed and implemented an attractive procedure for designing how to control the processes most likely to accelerate stream channel erosion as a result of urban development in a watershed. The method is broad and systematic, involving a set of recently developed tools and insights developed mainly in the 1990s about how to improve predictions of the effects of land surface alteration on hydrologic response and its effects on channel networks.

The power of the method arises from its combination of systematic field surveys, computer-assisted modeling, and capacity for efficiently examining alternative control strategies. The model-based approach provides transparency (assuming adequately thorough review) and reproducibility by various analysts. The field surveys allow for local calibration of the threshold conditions that destabilize channels, for checks of the realism of the model predictions, and for overcoming some of the limitations of the modeling approach through monitoring. The use of computerized tools for data storage and modeling allows cumulative watershed effects to be analyzed for an entire channel network, long weather records to be utilized in the computations, and for alternative control strategies to be reviewed efficiently.

The conceptual model underpinning the method incorporates modern ideas about the value of simulating continuous flow records to reflect watershed and channel geometry, watershed surface, and the recorded probability distribution of rainstorms. It also incorporates the idea, widely observed in all but large, perennial, vegetation-free sandy channels, that some critical threshold discharge is required to initiate channel erosion, either by mobilizing the bed or attaining a high enough stage to scour the weaker sediments of the channel bank. The method also recognizes from the literature of the 1990s that since urbanization causes significant flow increases even in frequent, moderate storms that the frequency and duration of the enhanced flows must be taken into account. Thus, instead of simply computing the effects of urban development on selected "representative" or "dominant" instantaneous peak flows as in past practice, the consultants have focused on the large increases in the duration of small to moderate floods that are enhanced by urbanization. They examine the magnitude and duration of the resulting shear stress compared to a critical value assigned to represent the resistance of the bank material, and convert this excess shear stress to a value of work through multiplying by an index of flow velocity and integrating the results over the duration of the flows simulated from a long rainfall record. Having acknowledged that this approach of concentrating on the moderate, frequent storms is likely to account for most of the problem, I note that the research that has produced this result is based largely on modeling and does not yet have a strong empirical base (such as erosion surveys along channels after large storms), and thus there is one reason (among others to be described later) for continuing to monitor the watersheds of interest to keep track of unforeseen changes.

The calculations of average annual work at flows (shear stresses) above the critical value needed for bed or bank erosion are used to develop an erosion potential index, which is a ratio of post-development energy expenditure to pre-development energy expenditure at the same place. This erosion potential (determined by both upstream watershed conditions and climate and the extent and nature of watershed development) is related to the risk of channel erosion through logistic regression that incorporates the systematic field surveys. This step is innovative and crucial for assessing risk of channel destabilization. For this reason, I suggest that a follow-up analysis be made of the sensitivity of the results to various uncertainties that are implicit in the method. My suggestion is made because of the attractiveness of the method for assigning risk of watershed-scale effects.

The sensitivity analysis might include the following topics. At present the definition of "medium/high erosion" conditions or "unstable conditions" that are used for calculating risk by the logistic regression (Figures 3-5 and 3-6 in HMP) are not defined explicitly enough for external evaluation. It would be useful to find out how much operator variance exists in the field identification of the channel stability condition, and how this variance affects the prediction of risk. It would also be valuable to know how susceptible the method is to uncertainties in the flow modeling. There is a brief reference in the report to validation of the simulations against observed high flows and the results were encouraging. However, it should be recognized that the test was not a very demanding one. The three streams used for the modeling are all gauged, so that local data could be used for model calibration and then the validation occurred on the same stream that was used for the calibration. A more common and demanding test of model accuracy arises when the flow model is applied to predict flows in an ungauged basin (most basins), where significant errors usually arise in the prediction of individual hydrographs. I cannot anticipate whether this will cause large uncertainties in the erosion potential (which is averaged over many individual predicted hydrographs), but it would be interesting for future applications of the method to know how much uncertainty arises in predicting the risk of channel instability because of hydrologic prediction and field definition of channel instability.

In the case of the Santa Clara River basin, of course, there is a useful amount of local gauging data, and the method is being investigated as it applies to three representative subwatersheds before extrapolation to the entire basin, so there are favorable conditions for a limited degree of extension of the predictions outside of an observed range. However, there remains some uncertainty in the prediction, especially as it applies to future buildout conditions (as recognized by using the concept of risk), and this is where the systematic field observations will become valuable (see later).

There is some ambiguity in the original presentation of the method (HMP Figure 3-2 and equation 1) about whether or when the channel resilience is to be represented by the permissible flow velocity for the bank material or the critical shear stress (particle size) of the bed material. It is conceivable that this issue could be resolved on a segment-by-segment basis by qualified observers, who might recognize which of the indices is relevant to the particular site or to a particular flow range. However, it seems unlikely that such investment of labor will be possible for most applications. In the present case, on p. 51 of the *Technical Requirements Report*, this uncertainty seems to be resolved in favor of utilizing the bank material measure.

This emphasis on bank erodibility (or even bed erodibility) reflects the relevance of the assessment methodology for channels and reaches in which the primary effect of urbanization is to increase channel size, degrade beds and undermine banks, as appears to be the case in the target basins (from the field assessments). The consultants have quite reasonably avoided trying to develop a more complete methodology based on sediment transport routing, because the state of that art is not adequate to the task of developing a robust design methodology for runoff and sediment control in whole watersheds and channel systems. However, this results in a slight overstatement of the conceptual basis for the assessment methodology when the report states (HMP p. 3-2) "The stability assessment looks at the balance among flow energy, *sediment supply*, and channel resilience that exists in a stable stream." The reason for highlighting this subtle point is that, because it cannot explicitly represent sediment supply and sediment transport capacity, the method is likely to 'overlook' a condition where sediment eroded from an upstream reach because of flow enhancement leads to aggradation where the channel gradient decreases suddenly downstream. In such a reach, the channel bed is often inundated with finer sediment or even becomes filled completely with sediment and the flows spread across the valley floor, sometimes causing bank undermining or tree mortality where, in the absence of the upstream sediment supply, the channel gradient would have maintained a low erosion potential even under the enhanced flow regime. Fortunately, the availability of computer tools already used in the method could be used to search systematically for reaches where this aggradation might be a problem. The software used for setting up the HEC-HMS modeling could be used to search channel networks for reaches with strong decreases in gradient downstream of reaches with a high risk of channel instability. These sites could be flagged for more detailed analysis and monitoring.

I also suggest that some further thought be given to expressing more explicitly the likely consequences of buildout in the watershed. This is not so much a technical aspect of the methodology itself, but of how its results are to be used and communicated. For example, HMP (p. 3-18) suggests a target value for managing flows to keep the erosion potential below 1.2. It is stated that under such a circumstance, "the chances of a stream becoming unstable are 14 in 100 or less." It would be illuminating to follow this brief remark with a fuller description of the likely outcomes. Presumably, the result is implying that 14 percent of all the reaches for which the erosion potential rises to about 1.2 could become unstable. How many miles of channel are likely to be involved? Where are these unstable reaches most likely to be? How many are close to sharp reductions of channel gradient, where aggradation might set off a cascade of other consequences? Elaboration of these points could improve the use of the results by decision-making bodies.

Finally, not only have the consultants developed a useful prediction tool for planning and design of control measures, but they have also established a valuable database of systematic channel surveys throughout the sampled subwatersheds. These data, especially the reach-by-reach definition of the degree of channel 'stability' (subject to the earlier suggestion about clarifying this definition), could be used as a way of monitoring both the condition of the channel network during watershed development and, later, as a means of evaluating the prediction methodology itself. A small outlay of funds for a rapid survey every few years and after major floods could yield a lot of useful data for watershed management and even timely channel restoration if damage should occur. For this reason, attention should be paid to storing the field survey data in some easily accessible form.

Thomas Dunne

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Los Angeles Basin

# Water Augmentation Study
# Phase II Final Report

The Los Angeles and San Gabriel Rivers Watershed Council

Prepared with assistance from Geomatrix Consultants, Inc.

August 2005

Funding for this project to date has been provided in part by a grant from the CALFED Bay-Delta Watershed Program (CALFED Agreement No. 4600001727), administered by the California Department of Water Resources, and by the following cost-sharing partners:

- California Department of Water Resources
- City of Los Angeles Department of Water and Power
- City of Los Angeles Watershed Protection Division
- City of Santa Monica Environmental Programs Division
- Los Angeles County Department of Public Works
- Metropolitan Water District of Southern California
- Regional Water Quality Control Board – Los Angeles
- US Bureau of Reclamation
- Water Replenishment District of Southern California

Additional funding for this project has been provided through a contract with the State Water Resources Control Board (SWRCB) pursuant to the Costa-Machado Water Act of 2000 (Proposition 13) and any amendments of this document thereto for the implementation of California's Nonpoint Source Pollution Control Program. The contents of this document do not necessarily reflect the views and policies of the SWRCB, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

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## EXECUTIVE SUMMARY

The *Los Angeles Basin Water Augmentation Study* is a long-term research project led by the Los Angeles & San Gabriel Rivers Watershed Council, to explore the potential for reducing surface water pollution and increasing local water supplies by increasing infiltration of urban storm water runoff. The Watershed Council has forged a unique partnership between local water supply, wastewater and public works agencies, the Los Angeles Regional Board, the California Department of Water Resources, and the US Bureau of Reclamation, which are jointly funding the study. Each partner contributes its own perspective to the shared concerns of bringing scientific evidence to bear on the feasibility of promoting infiltration without impacting groundwater quality. The study addresses a number of questions intended to better characterize the benefits of storm water capture for infiltration, including impacts on groundwater quality and assessing appropriate and most favorable geographic, geologic and hydrologic conditions for infiltration. The overall goals of the study will be to evaluate the costs and benefits of implementation, and determine the most effective strategy for developing this potentially significant source of water for southern California.

The focus of the early phases of the study was to monitor the fate and transport of runoff-borne pollutants by measuring storm water quality at the surface, as it infiltrates through the soil to groundwater. Phase I of the study focused on water quality assessment on single parcels utilizing infiltration structures, by monitoring two locations for one wet season. Phase II, just completed, expanded the monitoring in time and scope, adding new sites with different land uses and infiltration techniques, and monitoring all six sites for several years.

### Monitoring Program

Monitoring sites are located throughout the Los Angeles area and include two industrial sites, an elementary school, a commercial office building, a private residence and a public park (see Figure 2 – Monitoring Site Locations). Groundwater depths range from 20 feet to over 350 feet below ground surface. All sites were retrofit with various infiltration structures, ranging from simple landscaped swales to large-scale underground infiltration fields. Monitoring equipment was installed as part of the study, including soil water samplers (lysimeters) installed beneath the ground surface and groundwater wells.

The monitoring program consisted of taking storm water runoff samples during storm events, and taking post-storm vadose zone samples from lysimeters and groundwater samples from monitoring wells. Samples were sent to a state-certified laboratory for analysis. Constituents analyzed included general minerals, metals, oil and grease, perchlorate, some pesticides, volatile and semi-volatile organic compounds, NDMA, surfactants, and bacteria.

The four years of monitoring saw a wide range of rainfall variability, from the driest year on record (2001-2002) to the second wettest year on record (2004-2005). Rainfall varied geographically as well, with total rainfall amounts in 2005 ranging from about 22 inches at the park to over 37 inches at the Sun Valley industrial sites.

## Summary of Water Quality Results

Soil appears to be very efficient at removing bacteria from stormwater. Fecal coliform and E. coli were detected in at least one stormwater sample from each site except Hall House, and total coliforms were detected at high levels in nearly all stormwater samples at all sites. With the exception of one sample at the Broadous School, bacteria were not detected, or detected at very low concentrations, in lysimeter and groundwater samples.

Concentrations of metals tended to be higher in stormwater than in subsurface water samples. Concentrations in subsurface samples were variable and generally stable or decreasing. Exceptions are increasing trends of copper in lysimeter samples collected at the Sun Valley site that could be associated with infiltration of storm water with relatively higher concentrations of copper. Most inorganic groundwater quality constituents do not show clear trends or show decreasing concentrations over the study period. In only one instance, involving low concentrations of nitrate, did concentrations of a constituent show a statistically significant, although slight, increase. Groundwater quality data from the shallow groundwater sites show groundwater quality improvement (decreasing salt concentrations) potentially associated with dilution by infiltrating stormwater.

At the non-industrial sites the concentrations of general monitoring parameters such as TDS and chloride tended to be less than or similar to concentrations in lysimeter and groundwater samples. This suggests that the infiltration of stormwater is not likely to have a significant negative impact to groundwater from these constituents. At the Veterans Park site, concentrations of TDS, nitrate, chloride, and other salts in groundwater samples (including pre-infiltration background samples) was much higher than concentrations in stormwater samples. This result is likely due to historical application of fertilizers. Data collected to date suggest that concentrations of many of these constituents in lysimeter and groundwater samples are decreasing with time, possibly due to dilution by infiltrated stormwater.

Other than acetone, VOCs and SVOCs detected in storm water are different than VOCs detected in subsurface samples. VOCs detected in groundwater samples during the monitoring period were also detected in initial background samples. With the possible exception of occasional low level detections of acetone, VOCs in stormwater do not appear to impact groundwater at all. At the industrial sites, groundwater constituents such as MtBE and chlorinated solvents were present in some lysimeter samples at greater concentrations than present in any stormwater samples. This finding suggests the presence of subsurface contamination prior to stormwater infiltration.

The industrial sites had detections of more organic compounds and higher concentrations of metals than the non-industrial sites. The filtration system in the detention basins at Sun Valley and the Metal Recycler site was somewhat effective at reducing concentrations of certain constituents, particularly the dissolved metals. For example, at the Metal Recycler site, concentrations of dissolved arsenic, copper, chromium VI and lead were lower after filtration. The sedimentation basin at Veterans Park and the soil layers at the other sites would also be expected to reduce concentrations of metals and other solids, although effluent was not analyzed separately to verify this.

Although perchlorate was detected in some stormwater samples, there is no evidence of groundwater degradation by perchlorate from stormwater infiltration during this study. The occurrence of perchlorate in stormwater samples was unexpected, as the focus is typically on subsurface sources of perchlorate contamination. Perchlorate is a salt, which in addition to being a component of solid rocket fuel, is also an ingredient in fireworks and road flares. Other constituents of concern for groundwater (disinfection byproducts, 1,4-Dioxane, PAHs and DBCP) were not detected in stormwater.

Soil samples collected from four of the sites at the conclusion of the study indicated no significant increases in parameters monitored, and in many cases constituent concentrations were reduced.

The concentrations of many constituents vary throughout the sampling period, but there is no apparent pattern that can be tied to effects from infiltration. As stated above, VOCs detected in groundwater are routinely different than those in stormwater. VOCs detected in groundwater samples collected during the storm season were also detected in pre-season background samples, thus they do not appear to be the result of infiltration. Given the depth to groundwater at the two industrial sites and at Broadous, it seems unlikely that constituents introduced into the soil from stormwater infiltration would migrate all the way to the groundwater at a detectable concentration.

Data collected to date indicate that there is no statistically significant degradation of groundwater quality from the infiltration of stormwater-borne constituents. Groundwater quality has generally improved for most constituents at sites with shallow groundwater.

The data collected during this study show no immediate impacts, and no apparent trends to indicate that storm water infiltration will negatively impact groundwater at these sites. While variations in storm water and groundwater pollutants between types of land use were apparent, they may not be a barrier to infiltration. Filtration methods employed at the industrial sites seemed to be effective at removing certain pollutants prior to entering the infiltration system, which may make infiltration more feasible at these more polluted sites. Careful site characterization of surface and soil constituents at industrial sites should be conducted prior to implementing infiltration strategies.

While it is clear that site-specific conditions must be considered when urban runoff is being investigated for recharge as potable groundwater, it is also important to note that groundwater recharge offers a number of benefits to municipal water managers. Groundwater storage is less costly in terms of construction costs, environmental impacts, evaporation loss of water, and eutrophication as compared to surface-water reservoirs. Further, recharging groundwater puts the resource in closer proximity to the end-user than pumping water from reservoirs, an additional cost savings. With proper planning and research, the use of urban runoff for recharge of groundwater offers a viable alternative to relying solely on purchased water for such activities, water that may not be available in present quantities for purchase in the future. On average, over 500,000 acre-feet of runoff flow to the ocean from the Los Angeles County basin each year. If some portion of this water can be captured for reuse, the pressure on supplies in northern and central California may be moderated.

## Next Steps

### Long-term Monitoring Program

While the data collected during this program do provide significant information, monitoring will continue in order to better assess the cumulative effects of infiltration. A reduced program of subsurface monitoring is under currently development. This program will likely include annual or bi-annual monitoring of lysimeters and groundwater wells at four or five sites. No storm water samples will be collected, as surface runoff quality has been well-characterized at these sites. Monitoring will be scheduled after significant storm events and late in the storm season, to ensure that infiltration to the deepest lysimeters has occurred. The analytical suite will be reduced but should include metals, general parameters, some organics, and perchlorate. We expect to continue monitoring for at least two additional years, and possibly longer if funding is available.

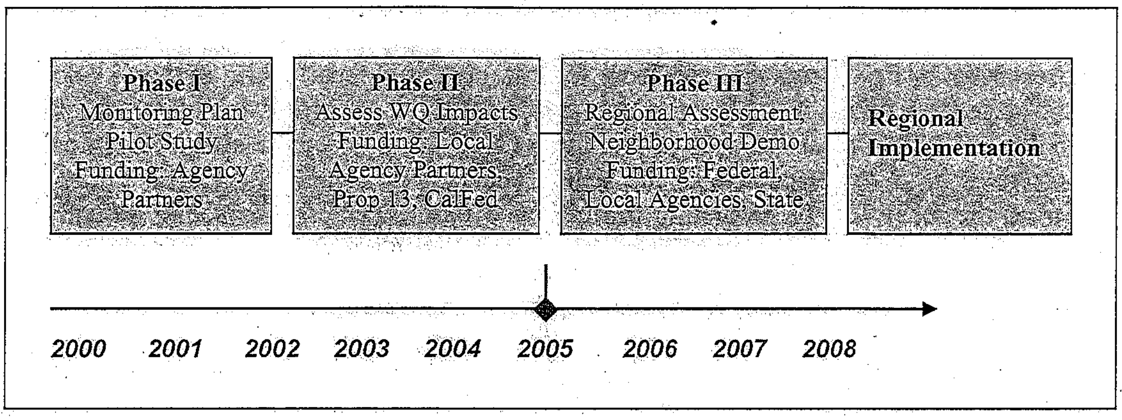
### Phase III Work Plan

The third phase of the study will incorporate demonstration projects on a neighborhood scale. We propose to retrofit one or more small neighborhoods with state of the art Best Management Practices to address storm water infiltration as well as water conservation, pollution reduction and treatment, flooding, and habitat and stream restoration. Specific techniques will depend upon the sites selected, but may include conversion to native drought-tolerant landscapes, use of irrigation controllers, facilities to capture runoff for infiltration and/or reuse, restoring buried stream channels, and adding green space and habitat areas. The demonstration projects will be monitored for water quality as well as for reduction of runoff and water use, changes in property values, and other potential benefits. These neighborhood projects will provide real-world models of addressing existing infrastructure and will serve to integrate many on-going efforts in the region to address flood management, water quality, water supply and environmental restoration. Our goal is to demonstrate how these approaches can be applied on a regional scale in Southern California as well as in other geographic regions.

In addition to the demonstration project, we are assessing the overall feasibility of utilizing infiltration techniques to capture storm water for groundwater recharge. The Bureau of Reclamation is currently developing a groundwater augmentation model to predict the amount of additional water that could be available for deep percolation if infiltration is increased. They are also developing a regional cost and benefit assessment to determine the real cost of this new water supply. Researchers at UC Riverside are assessing costs on a site-specific scale. The long-term goal of this project is a regional strategy for implementation.

The WAS is in its fifth year and is currently funded through 2006, through the second year of Phase III. The figure below illustrates each of the project phases, the goal of each, and source of funding.

**Project Timeline**



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# 1. INTRODUCTION

## 1.1 Project Background

The Water Augmentation Study (WAS) is a ten year research program of the Los Angeles and San Gabriel Rivers Watershed Council (Watershed Council). The purpose of the program is to assess whether the capture and infiltration of stormwater at localized sites throughout the region is a viable means of augmenting water supply, without adversely affecting groundwater quality. The study began in 2000 in collaboration with representatives from academia and from federal, state and local public agencies. Several public agencies joined in a Memorandum of Understanding (MOU) to support the WAS, and formed a Technical Advisory Committee (TAC) to oversee the study. Each partner contributes its own perspective to the shared concerns of bringing scientific evidence to bear on the feasibility of promoting infiltration without adversely impacting groundwater quality. For Phase I, the TAC developed the monitoring program and provided oversight for the Pilot Study. For Phase II, a new MOU was signed and the TAC has continued to provide oversight and technical input on a number of program aspects. A third MOU was approved by seven of the agencies, to continue the partnership for Phase III of the study. The TAC currently consists of the Watershed Council and the following agency partners:

- City of Los Angeles Department of Water and Power
- City of Los Angeles Watershed Protection Division
- City of Santa Monica Environmental Programs Division
- Los Angeles County Department of Public Works
- Metropolitan Water District of Southern California
- United States Bureau of Reclamation
- Water Replenishment District of Southern California

## 1.2 Project Goals

This study addresses a number of questions intended to better characterize the benefits of stormwater capture for infiltration. The most important aspects initially are evaluating the potential impact on groundwater quality, and assessing appropriate and most favorable geographic, geologic and hydrologic conditions for infiltration.

The focus of the early phases of the study was to monitor the fate and transport of runoff-borne pollutants by measuring stormwater quality at the surface, as it infiltrates through the soil and as it mixes with groundwater. Phase I of the study focused on water quality assessment on single parcels utilizing infiltration structures, by monitoring two locations for one wet season. Phase II, just completed, expanded the monitoring in time and scope, adding new sites with different land uses and infiltration techniques, and monitoring for several years. The specific goals of Phase II were to assess the cumulative impact of



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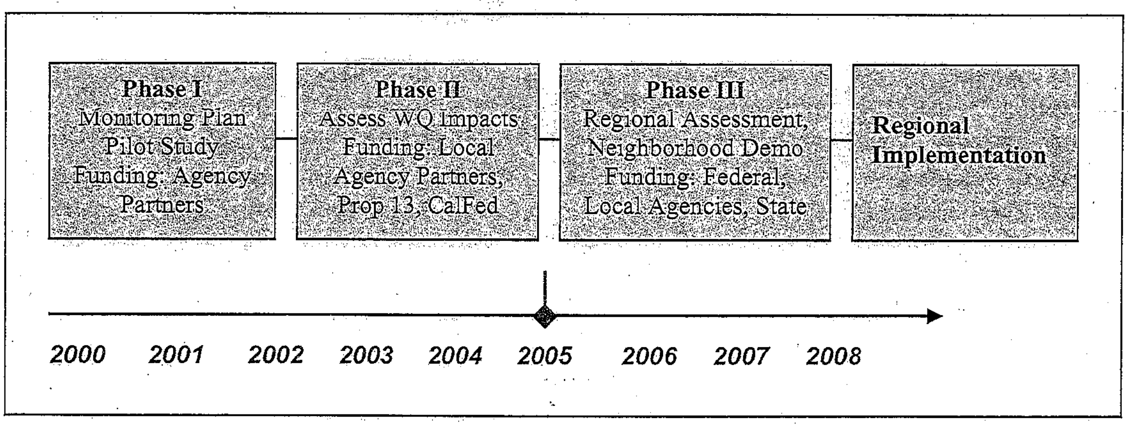
infiltration on soil and groundwater, and evaluate the effects of different land uses on pollutant types and concentrations.

During Phase III of our research we will assess through modeling how much additional groundwater recharge may be possible, and whether the additional recharge could provide sufficient water supply to offset the cost of implementation and extraction compared with the cost of developing new water supplies. We will implement one or more demonstration projects on a neighborhood scale, incorporating both infiltration and water conservation strategies. We will also assess other potential benefits and barriers (environmental, regulatory, social, and economic) to determine the best strategy for regional implementation.

The WAS is in its fifth year and is currently funded through early 2007, through the third year of Phase III. **Figure 1** illustrates each of the project phases, the goal of each, and source of funding for each phase.

**Figure 1**
**Project Timeline**




## 1.3 Project Activities during Phase II

### 1.3.1 Meetings

TAC meetings were held generally bi-monthly, for a total of eighteen meetings between July 2002 and April 2005. Members of the TAC include the agency funding partners, and representatives from the California Department of Water Resources, Los Angeles Regional Water Quality Control Board, Upper Los Angeles River Area Watermaster (ULARA), Main San Gabriel Basin Watermaster, West and Central Basin Municipal Water District, Santa Ana Watershed Project Authority, UC Riverside and TreePeople. Minutes were distributed to all TAC members.

Plenary meetings, open to all interested parties, were held periodically when there was a desire to communicate project progress to a larger audience. During Phase II, two plenary meetings were held: in February 2003 and November 2004. Presentations at the first meeting included an update on Phase I and II monitoring, related activities in the Santa Ana Watershed Project Authority, and a presentation/discussion of preliminary plans for Phase III of the WAS. In preparation for that meeting, a 4-page color flyer was developed describing the long-range goals and timeline for the study. The second plenary meeting addressed results to date from Phase II monitoring, development of the runoff/infiltration model to quantify potential for new water supply from infiltration, and a presentation by the Sanitation Districts of LA County on the results of their Soil Aquifer Treatment study. The latter is a long-term collaborative research study to assess the impacts on groundwater quality of infiltrating treated wastewater in recharge basins.

### 1.3.2 Sample Collection

During the first year of Phase II (2002-2003), three sites were monitored: an elementary school, a commercial office site, and a single-family residence. Samples were collected over four storm events during that winter, between November and April. The field monitoring program was conducted by CDM, under contract to the Watershed Council. Three new monitoring locations were established for the 2003-2004 season, bringing the total to six sites. The new sites were a public park in Long Beach and two industrial sites, in Los Angeles and Sun Valley. Geomatrix Consultants, Inc. (Geomatrix) of Costa Mesa was retained by the Watershed Council to establish the three new monitoring sites and conduct the field sampling program for two seasons from 2003-2005. For the new sites, they assisted with site selection and evaluation, designed and constructed infiltration BMPs, designed a monitoring program and installed monitoring equipment. For all six sites, they assisted with preparation of the Sampling Plan and Quality Assurance Project Plan. During the rainy season, they monitored weather forecasts and, in consultation with the Watershed Council, identified storms suitable for sampling and mobilized their field crews accordingly. Two to three rounds of sampling were completed for each site each season. Geomatrix was also responsible for managing and analyzing the resulting data.

### 1.3.3 Laboratory Analysis

The Watershed Council contracted with Calscience Environmental Laboratories in Garden Grove, California to perform soil and water quality testing of field samples during the course of the study. Calscience provided sample checklists, labeled sample containers and coolers for each monitoring site and event. Samples were delivered to Calscience by sampling field staff after collection. Laboratory results and quality control data were transmitted to the Watershed Council and Geomatrix electronically and via hard copy reports. These data are included in the Appendix tables for each monitoring site.

### 1.3.4 Equipment Maintenance

Each monitoring location has a variety of equipment installed for infiltration and monitoring, including detention/sedimentation vaults, soil water samplers (lysimeters), groundwater monitoring wells, and subsurface soil moisture sensors. These are described in detail in the Project Study Plan (Section 3). Maintenance activities included inspecting all facilities and equipment, testing the lysimeters, cleaning out the sedimentation vaults, collecting soil moisture data and replacing the datalogger batteries as needed.

During the course of the study, several lysimeters and well covers were damaged and replaced, and one lysimeter was relocated to provide a more representative sample from the vadose zone. We also installed a deep lysimeter (70-80 feet below ground surface) at one of our industrial sites to better characterize the pollutant removal capacity of the soil.

We also prepared Operations and Maintenance documentation for the BMPs installed at our newest sites, as they will be maintained by the property owners once this project is complete.

### 1.3.5 Presentations

Presentations on the WAS were made at a number of conferences and meetings during this phase of the project:

- Association of American Geographers 2002 Annual Meeting
- Floodplain Management Association 2004 annual conference
- Headwaters to Ocean 2003 and 2004 annual conferences in Long Beach, organized by the California Shore and Beach Preservation Association, CalCoast, the Wetlands Recovery Project and the Society of Wetlands Scientists
- Los Angeles County Department of Public Works BMP Task Force
- Main San Gabriel Basin Watermaster, Water Quality Management Committee
- Public Officials for Water and Environmental Reform 2002 annual Water Policy Conference
- State Water Resources Control Board Nonpoint Source 2003 bi-annual conference
- Southern California Water Dialogue
- Southern California Stormwater Monitoring Coalition

We also presented periodic updates on study progress at the Watershed Council's monthly stakeholders' meetings.

## 1.4 Purpose of this Report

This report provides information on activities undertaken during the monitoring phase of the WAS, from July 1, 2001 through April 30, 2005, and the water quality results from that monitoring. The Introduction describes the WAS background and timeframe, and highlights the project goals and accomplishments. Section 2 is a literature review of prior research that addresses runoff characteristics and infiltration studies. Section 3 describes the project activities and work plan, including the monitoring sites, the protocols for the sampling regime and monitored pollutants. Section 4 discusses the monitored events and the water quality results, and Section 5 assesses the data gathered over the past four years and summarizes the conclusions from these results. Section 6 discusses project outcomes and what steps will be undertaken during the next phase. The Appendices (on the enclosed cd) include complete water quality and soil data results, trend analysis graphs, groundwater hydrographs and other technical data.

# 2. RELATED RESEARCH

This section reviews and summarizes the literature related to research on urban stormwater infiltration, including the long-term impacts of recharge on groundwater, and appropriate conditions for stormwater recharge.

## 2.1 Characteristics of Urban Stormwater Pollutants

### 2.1.1 The Nationwide Urban Runoff Program

Urban runoff is comprised of various flow phases and includes dry-weather base flows, stormwater, combined sewer overflows and, in applicable areas, snowmelt (Pitt et. al., 1996). Perhaps the most comprehensive study of the various constituents comprising urban stormwater pollution was undertaken by the U.S. Environmental Protection Agency's (EPA) Nationwide Urban Runoff Program (NURP). This research was conducted by the Water Planning Division of the EPA and entailed collecting and analyzing water sampling data between 1978 and 1982 in order to both determine the characteristics of urban stormwater runoff and to identify potential differences among contaminant concentrations attributed to varying land uses and geographic areas. EPA listed priority pollutants studied included heavy metals, organic pollutants, coliform bacteria, nutrients, oxygen-demanding substances, and suspended solids.

The NURP study entailed collection of runoff samples from 81 sites located in 22 different cities throughout the United States, and included more than 2,300 separate storm events. Concerning general levels of priority pollutants found in urban runoff, the NURP study identified heavy metals as the most prevalent substances, all 13 of which were detected in water samples. Lead, copper, and zinc occurred at the highest frequency, present in 91% of samples taken. The EPA noted that lead concentrations violated drinking water thresholds in 73% of the samples, though this does not necessarily mean that receiving waters (i.e. groundwater aquifers) would contain the same level of lead. Organic constituents -- 63 out of a total of 106 tested -- were detected at both lower concentrations and frequencies than heavy metals, occurring in no more than 20% of stormwater samples. Of these constituents, pentachlorophenol and chlordane exceeded the EPA's freshwater *acute* threshold, while freshwater *chronic* criteria were exceeded by pentachlorophenol, bias, phthalate, gamma-BHC, chlordane, and alpha-endosulfan. Detected carcinogens included alpha-BHC, gamma-BHC, chlordane, pyrene, chrysene, and phenanthrene. Rarely occurring organic constituents were speculated to be site-specific. Coliform bacteria were present in high levels in urban runoff samples. Nutrients, while found in runoff, appeared in lower concentrations while oxygen-demanding substances were detected in samples approximating levels found in secondary treatment plants (EPA 1983).

Finally, the EPA study concluded that total suspended solids concentrations present in stormwater runoff samples were higher in mineral and human-made products but lower in organic particulates than those discharged from sewage treatment plants. Suspended solids found in runoff tended to have other types of contaminants absorbed onto them. On an annual load basis, suspended solids contained in urban runoff greatly exceed those released from secondary treatment plants. Thus, contaminated sediments, at least in some areas, are an issue requiring address, as is the need for consideration of urban runoff control where total suspended solids-related water quality problems exist (EPA 1983).

The data for ten measured contaminants were used to calculate the event mean concentration, or EMC. The EMC is defined as the total constituent mass discharge divided by the total runoff volume for each measured substance, and is based on the flow weighted average concentration of each identified priority pollutant. Results indicated that the EMCs at each test site and the median of the EMCs for all test sites were found to exhibit normal statistical distribution, and that their appeared to be no significant correlation between EMC values and runoff volumes. This finding is best explained by the high incidence of pollutant concentration variability from one rainfall event to another at most sites, effectively eclipsing site-to-site variability that could be present as well as influences owed to variations in land use, geographic location or other relative factors (slope, precipitation, urban density). Essentially, although there are differences in the concentrations of various constituents across land uses, the data do not provide a statistically significant basis for predicting differences in EMC values (EPA 1983).

### 2.1.2 Other Studies

The 1983 NURP study was a landmark research project, yielding comprehensive data sets that allowed for general characterization of the various pollutant substances found in urban runoff. Since this published report, numerous other studies have been conducted to both measure and describe these and other identified constituents in stormwater. A brief examination of more recent studies reveals that there are additional constituents that require attention. In 1994, EPA released a study addressing potential groundwater contamination from stormwater infiltration. The agency noted that volatile organic compounds, including the subset polycyclic aromatic hydrocarbons (PAHs), have been discovered in groundwater near industrial sites. Further, viruses have been detected in groundwater adjacent to stormwater recharge basins.

Viruses are a special case to contend with for a number of reasons: 1) enteric viruses are more resistant to environmental factors than are enteric bacteria, 2) viruses can survive for longer periods of time in water, 3) they can occur in both fresh and marine waters in the absence of fecal coliforms or other indicator bacteria, and 4) they are more resistant to common disinfectants than indicator bacteria (EPA 1994). Viruses are not commonly monitored in stormwater because of the cost and volume of sample needed. Available studies indicate that viruses are sometimes present in dry weather and wet weather flow. Santa Monica Bay Restoration Commission study measured enteric viruses in storm drains in concentrations from 0 to 10 infectious units per 100 liters during dry weather (SMBRP 1992). A study by Caltrans found the presence of at least one type of human virus in 12 of 97 samples taken at 20 sites in Southern California (Schroeder et al 2002). Further, this study found no correlation between the presence of human virus and standard indicator bacteria.

Concerning other potential environmental pollutants, a group of known but yet unregulated constituents that can make their way into urban runoff include pharmaceuticals and personal care products (PPCPs). This diverse group of compounds is found in human and veterinary drugs, X-ray media, bioactive food supplements, fragrances, and sun-screen agents (Lee 2004). Lee predicts that as urban population bases expand, PPCPs will play an increased role in water quality issues, noting that chemicals in domestic water supplies are transferred to urban runoff through leaking sanitary sewers and fugitive irrigation waters. Lastly, the EPA recently identified disinfection by-product agents (DBPs) as a group of water pollutants. Various DBPs form when a chemical used for disinfecting drinking water reacts with natural organic matter or bromide/iodine in the source water. Commonly used disinfectants include chlorine, ozone, chlorine dioxide, and chloramine (Lee 2004).

Perchlorate, which has become a significant pollutant of concern in groundwater, is rarely sampled in stormwater. Perchlorate is a salt, which is used as an oxidizer to help solid rocket fuel burn, and is an ingredient in fireworks and road flares. A recent study (Tipton 2003) suggests there is the potential for perchlorate to be reduced in surface soils through natural biodegradation before it can migrate to ground water.

## 2.2 Impacts from Urban Runoff on Groundwater Quality

### 2.2.1 The NURP Study

The EPA NURP study also evaluated the effect of urban stormwater runoff on groundwater aquifers and subsurface soils at sites in Long Island, New York and Fresno, California. This evaluation was based on extensive monitoring of infiltration recharge basins ranging from recent installations to others that had been in service in excess of twenty years. The most significant of these findings are summarized below.

- Heavy metals, an appreciable number of organic priority pollutants, most pesticides, and coliform bacteria are intercepted during the process of infiltration and effectively prevented from reaching groundwater underlying recharge basins.
- Most constituents accumulate in the upper soil layers. Concentrations were found to correlate with the length of time a basin has been in service. Effective retention of applicable constituents takes place with all soil types tested, ranging from clays to sands. The depth of constituent penetration is affected by soil type and water content, depth to groundwater, slope, and various bio-chemical parameters; however, in no case did contaminant enrichment of soil exceed several meters in depth, with the highest concentrations found near the surface.
- The limit of the ability of soils to retain/absorb urban runoff constituents is unknown and additional study is warranted. A related issue is the environmentally safe disposal of sediments in detention basins.



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- At both NY and CA locations, groundwater surfaces were at least 20 feet below the base of the recharge basins. NURP findings may not be applicable at locations with shallow depths to groundwater.
- No significant differences in the interception or retention of runoff constituents were apparent for basins with vegetated versus non-vegetated recharge surfaces. However, vegetation does apparently help to maintain infiltration rates normal for the soil type.
- Surface soil accumulations of priority pollutants in installations used for both recharge and recreational use requires further investigation to determine whether such a practice creates unacceptable health risks or requires appropriately designed and conducted maintenance procedures.
- Urban runoff from central business districts and industrial sites, which were not included in the NURP study, may very well contain significantly higher levels of pollutants.
- Synergistic effects among urban runoff constituents were not examined. Various environmental parameters including temperature and pH may reduce or increase toxicity levels of particular constituents. More studies in this area are needed.

### 2.2.2 Recent Studies

Research conducted since the NURP study reinforces many of the general findings listed above. Most priority pollutants carried by stormwater sorb to soils, accumulating in the upper layers. Ferguson (1998) states that "the soil is a powerful filter and dynamic ecosystem that protects streams and aquifers from urban contamination." Metals, several pathogens, hydrocarbons, and numerous organic compounds will either: 1) sorb to soil particles, 2) volatilize at the surface, or 3) degrade by microbial processes in surface and sub-surface soil layers.

Two studies conducted in small residential communities in Wisconsin compared constituent levels in urban runoff samples with groundwater samples taken downgradient of drywells used for stormwater infiltration. Low levels of polynuclear aromatic hydrocarbons (PAHs) and volatile organic compounds (VOCs) detected in stormwater were not detected in groundwater with the exception of one well sample. However, sediment samples taken from the infiltration wells revealed that these contaminants were accumulating in the upper soil layers (Lindemann 1999, Dunning and Bannerman 1993). Similarly, studies of infiltration systems receiving highway runoff for several decades demonstrated the accumulation of heavy metals and hydrocarbons in the upper soil matrix much higher than those measured concentrations in nearby soils (Dierkes and Geiger 1999, Mikkelson et al 1997, Legret and Colandini 1999). In these studies, groundwater below infiltration systems was not impacted.

While the general consensus is that stormwater infiltration poses few significant risks to underlying aquifers, adverse impacts to groundwater from runoff infiltration can take place. Fisher et al (2003) compared ambient groundwater quality to that receiving infiltrated runoff in 16 detention basins located in southern New Jersey. The basins differed in surface area, depth, and number and size of inlets and outlets but all were located in newly developed urban areas. Analyses of water samples taken from installed wells indicated elevated levels of four pesticides in runoff, lower levels of dissolved oxygen (DO) in groundwater under infiltration basins (a probable result of increased microbial activity due to greater concentrations of organic compounds in runoff), and greater occurrence of petroleum hydrocarbons. Infiltration rates among the 16 basins varied due to accumulated sediment near inlet channels and at low points in the basins. The researchers note that because low concentrations of DO can affect both the persistence and transformation of other polluting substances, the groundwater quality beneath detention basins can be adversely impacted by the influx of large volumes of poorly oxygenated stormwater. Hence, infiltrating stormwater can, on the one hand, serve to dilute pollutants of concern but can also increase the occurrence of other substances above the amounts found in ambient groundwater.

In four other studies described here, reported results support most of the NURP findings, but each also points out select issues concerning the use of urban runoff to recharge groundwater aquifers. In a study taking place in Lyon, France, researchers took water and soil samples from an infiltration basin in operation for over 30 years, located on a university campus in an urban area. The basin has a partially clogged cobble layer contaminated by hydrocarbons and heavy metals (owed to its extended use). The groundwater table fluctuates between 2.5–3.5 meters below the surface of the infiltration bed. Results for priority pollutants concentrations in infiltration bed sediments were similar to those reflected in other studies, with reduced concentrations found at depth. However, mineralization of organic compounds originally retained in detention basin sediments acted as a source of dissolved contaminants, being attributed to elevated concentrations of phosphate and dissolved organic carbon in receiving groundwater (Datry et al 2004). The problem of reduced DO in urban runoff transferring to groundwater was reiterated in this research project. A similar study of the same basin concluded that discrepancies can occur when evaluating the contamination potential from analysis of nutrient concentrations in inflow stormwater and the environmental risk resulting from percolation of inflow water through permeable sediment (Datry et al 2003).

In another study, Barraud et al (1999) measured various urban runoff constituents in both newly built and 30 year-old detention basins in Valence, France. These basins drain runoff from heavily traveled roads and open space, and the bottoms of each are very close to the water table. Results indicated that some organic constituents were not being retained in bed sediments but rather were part of the washdown at the beginning of infiltration, due to a permanent saturated soil layer in both shallow basins. Bottom soil was contaminated by hydrocarbons but this is not surprising given the shallow depth of the basins. The authors point out that the sediment bed of the older detention basin (~30 years) was contaminated with heavy metals and mineral oils impacting at least a one meter radius of soil. In another study, also examining the spatial distribution of constituents in a 14 year-old constructed infiltration basin located in France, researchers noted that zinc, a highly mobile heavy metal, was found below 30 centimeters of top soil—the depth limit of other metals reported in other studies (Dechesne et al 2004).

In a comprehensive review of groundwater contamination literature concerning urban runoff constituents, Pitt et al (1996) reaffirmed most of the findings of studies previously discussed. Additionally, the authors state the following:

- Viruses, in low levels, may be found in stormwater and small amounts can cause health problems. Most viruses do die off or adsorb to soil, and most are removed within the first few meters. However they are so small that they could be transported through cracks or through very permeable soils to underlying groundwater. The highest probability of transferring viruses from the surface is where the aquifer is near the surface.
- Nitrogen contact with soil can lead to nitrate leaching. Nitrates are quite soluble and will stay in solution in percolating water migrating to groundwater.
- Heavy and repetitive use of mobile pesticides on irrigated or sandy soils can contaminate aquifers. Pesticides decompose at different rates on soil surfaces but can take much longer to degrade in subsurface soils due to reduced microbial activity. Pesticide leaching into the vadose zone and groundwater is a possibility.
- Sorption of organic constituents can be countered by resolubilization during wet periods. Factors affecting microbial degradation include temperature, pH, soil moisture content, ion exchange capacity of soil, and air availability.

It should be noted that Pitt's evaluation of constituent transport potential was based on the worst case scenario: sandy soils with low organic content overlying shallow water tables. Most organic compounds would be less mobile through soils having a higher proportion of clay and organic matter. Natural organic matter also impacts sorption of metals in soil. In laboratory simulations, high concentrations of organic matter, particularly humic acid, were found to react with heavy metals and increase metal attenuation in soil (Hathhorn and Yonge 1995). Essentially, extremely coarse or extremely clay-rich soils may not filter constituents as well as more medium-grained soils with organic content.

### 2.2.3 Federal Agency Studies of Groundwater Recharge in California

The United States Geological Survey (USGS) has been involved in artificial recharge of aquifers in the state of California since the 1960s, when the California Water Plan was approved to import water from the northern part of the state and deliver it to the southern area for subsurface storage via recharge. Prior to USGS involvement, the state had been engaged in utilizing stormwater for recharge of groundwater through the use of spreading basins since the early 1900s (USGS 2001). Currently, the central and west coast groundwater basins in Los Angeles County are artificially recharged using three sources of water: 1) purchased water originating from northern California and the Colorado River, 2) treated recycled water purchased from the Los Angeles County Sanitation District, and 3) diverted stormwater runoff. The urban runoff that is used is directed to holding ponds located at the Rio Hondo and the San Gabriel River Spreading Grounds, in Montebello and Pico Rivera. The Water Replenishment District (WRD) of Southern California reports that average annual use of potable water in the area is 250,000 acre-feet, while average annual recycled and stormwater use are 50,000 and 40,000 acre-feet, respectively (WRD Fact Sheet). The USGS has conducted a multitude of studies to further the understanding of the processes involved in recharge, the most relative of which are summarized below.

Concerning the fate and transport of pathogens in recharge projects, Metge (2002) notes that temperature, salinity, DO, pH, microbial size, nutrient availability, and microbial growth are factors that influence the survival of most pathogens in groundwater matrices. Many viruses become inactivated at temperatures above 200°C but can survive below 100°C. A USGS-developed model indicated that the degree of aquifer heterogeneity assisted in determining the degree of viral transport within the soil matrix. In another USGS study examining the same issues at a research site in Montebello, researchers found that coliform bacteria increased rapidly and immediately after recharge using treated wastewater, noting that bacteria can move quickly through underlying soil, within a matter of days. Further, using a proxy medium (in replacement of a live virus) and bromide as a tracer for assessing the subsurface transport of the virus in three separate periods of time Anders et al (2003) found that adsorption was the predominant removal mechanism during recharge processes. Here, higher temperatures and changes in entrapped air, sealing of the soil surface, and the effect of biofilms sealing soil matrix pore space were the determining factors. In one other study, USGS researchers determined that untreated groundwater located in Los Angeles area basins containing low-levels of volatile organic compounds (VOCs) was most likely contaminated by industrial wastewater that was recharged into forebay areas. Most of the wells with high concentrations of multiple VOCs were located in close proximity to recharge facilities, with VOC concentrations dropping off beyond 10-15 kilometers in distance. Hydrology and the acceleration of groundwater flow produced by recharge actions in conjunction with pumping are likely factors in controlling the distribution of VOCs (Shelton et al 2001).

Finally, in what might be considered the most comprehensive assessment of artificial recharge using tertiary-treated wastewater, a 10-year study was recently completed by USGS, Los Angeles County Sanitation Districts and others to assess water quality at recharge facilities in Montebello Forebay. A research basin was constructed adjacent to spreading grounds in Pico Rivera for a limited number of tests and analyses of samples taken at deep-seated monitoring wells located up to ten miles from the basins was also carried out. Results of this study are summarized below:

- At the research basin, DOC and dissolved nitrogen in percolating water significantly decreased. The decrease in DOC was independent of operating conditions. Reduced nitrogen in subsurface recycled water was attributed to the oxidation of nitrogen to nitrate, with denitrification taking place as the environment becomes more reducing.
- Experiments using tracers and employing extrapolation from results indicate that viruses die off or become inactive over a distance of about 100 feet from Montebello Forebay, meeting current DOHS requirements. No infective viruses were detected in groundwater samples.
- Removal of organics occurs mostly within the top 10 feet of soil.

It should be noted that recharge has also been implemented in the central portion of California since 1956, when the Fresno Metropolitan Flood Control District constructed a multi-use flood control system comprised of 143 stormwater ponding basins and five large flood-control dams and reservoirs. Each watershed located in the Fresno-Clovis metro area is approximately one square mile in area and is served by a basin ranging in size from 10 to 40 acres, with a holding capacity of between 100 and 600 acre-feet of water. Studies conducted by the District indicate that ponding basins remove between 50% - 83% of commonly occurring runoff constituents. On an annual basis, about 17,000 acre-feet of stormwater are recharged back into local aquifers providing potable water. Thirty basins serve community recreational activities (sport fields, dog runs, open space). According to Mr. Daniel Rourke of the Fresno Flood Control District, most basins are cleaned every 4-5 years, with some being cleaned at a higher frequency due to lower infiltration rates (pers. comm. 2004). In addition to the studies conducted of these basins under NURP, another USGS study of an industrial catchment in Fresno found that contaminants do not reach groundwater but tend to accumulate in the surface sediments (upper 1.5 inches). Concentrations of stormwater constituents in soil decreased with depth and reached background concentrations at depths of only 6.3 inches (Schroeder 1995).

## 2.3 Constituent Concentrations and "First Flush"

The "first flush" effect describes an initial storm event whereby build-up of constituents during dry periods are flushed from urban surface areas by runoff. During these first flush periods, very large quantities of constituents are discharged into receiving waters, or alternatively, into retention basins. Within a given storm event, there may also be a "first flush" effect as constituents are initially washed off. Urbonas and Stahre (1993) note that as rainfall continues, surface constituent build-up is depleted and concentrations are diluted by larger flow volumes. The amount of surface constituents washed off also depends on the intensity and the duration of the storm event, the size of the watershed area being drained, the amount of impervious area, and the frequency of dry weather periods. Ferguson (1994) found that with storms of long duration, initial runoff had higher concentrations of constituents than runoff generated later in the storm. In a study conducted by the Southern California Coastal Water Research Project (SCCWRP), the effect of rainfall intensity and duration on contaminant concentrations in runoff was assessed by sampling simulated events of varying rainfall intensities. Within a given storm, concentrations of suspended solids, total and dissolved metals and polycyclic aromatic hydrocarbons (PAHs) in runoff were consistently greater at the beginning of the storm events (<10 minutes) than later in the event (10-40 minutes). Variability between storms indicated that constituent concentrations were inversely correlated with rainfall duration or intensities: shorter rainfall durations or lower rainfall intensities produced greater runoff concentrations (Tiefenthaler and Schiff 2002).

The variation in constituent concentration within a storm has implications for treatment and monitoring. If the beginning of the storm contains the highest concentration of constituents, the total volume requiring pretreatment may be considerably less than the total storm runoff. For monitoring purposes, composite samples with results reported as

EMCs become a more consistent measure than single grab samples taken at a random point during the storm event (Strecker 1994).

In addition to constituent concentrations during a storm event, Urbonas and Stahre (1993) discuss whether early season storms constitute the only "first flush", containing higher concentrations of constituents than later storm events. In arid regions, such as southern California, there may be several dry weeks between storm events. These dry periods allow constituents to accumulate repeatedly, impacting constituent concentrations in subsequent storms. Thus, there may be multiple "first flush" events throughout the season. In a study conducted by SCCWRP to assess the relationship between antecedent rainfall and pollutant build-up, researchers found that virtually all of the accumulation occurred within one month after wet weather for total suspended solids, total trace metals, and dissolved trace metals (Tiefenthaler et al 2002).

## 2.4 Constituent Removal Effectiveness of BMPs

The utilization of urban runoff for artificial recharge of groundwater may necessitate pre-treatment to maximize the removal of as many constituents as possible prior to release for infiltration. Structural best management practices or BMPs can be very effective at removing constituents from stormwater runoff prior to infiltration. Pre-treatment associated with many types of BMPs can significantly reduce the potential for adverse groundwater impacts (Schueler 1987). Some of the more common BMPs employed include the following:

- Sedimentation or settling of suspended solids, which removes particulates and sorbed constituents such as metals, hydrocarbons and nutrients
- Filtration to remove particulates and associated constituents. Organic filtration media can also remove soluble nutrients
- Biological uptake or degradation by plants and microorganisms is effective for removing nutrients and toxic organic compounds. Sedimentation basins, ponds, and wetlands promote degradation and/or volatilization of certain organic compounds (EPA 1999).

Most often, simple filtration through soil is the BMP most often used to naturally treat urban runoff for recharge. As previously discussed, infiltration is appropriate for areas that have relatively permeable soils. However, Lee (2000) cautions that the very soils that are conducive to filtration of heavy metals, hydrocarbons and most bacterial pathogens perform poorly in filtering and adsorbing contaminates that might otherwise enter an aquifer. Additionally, clogging of infiltration beds restricts maximum performance. Lee reports that current guidelines for effective infiltration call for minimum soil permeability rates of about .52 inches/hour. For this and other stated reasons, a groundwater monitoring element is suggested to ensure that water quality is not impaired in receiving groundwater.

On a local level, the County of Orange, California, commissioned a study to determine the most appropriate BMPs to comply with federal regulations included in the County's stormwater permit. Based on runoff pollutant reduction rates and maintenance requirements, infiltration basins and trenches were among seven BMPs deemed feasible for implementation (RBF 2003). In another study, researchers examined the long-term effectiveness of four types of permeable pavement systems comprised of a matrix of concrete or plastic structures with spaces filled with sand, gravel, or soil constructed within a parking lot in Renton, Washington. Results demonstrated that stormwater effectively infiltrates through the voids into underlying soil in the four permeable pavement systems used, and that all showed only minor signs of wear and tear after six years of use (Brattebo and Booth 2003). A study conducted in Mexico found that untreated wastewater used for irrigation did not significantly impact groundwater, with the exception of nitrates (Downs et al 2000). The reservoir and canal system served as vehicles for volatilization, degradation, and filtration of dozens of measured contaminants including metals, semi-volatile organics and pesticides.

The effectiveness of BMPs varies with local weather conditions, the nature and concentration of targeted constituents, and geologic parameters of the individual site. Local, physical conditions that can make stormwater infiltration inappropriate include steep slopes, slow percolating soils, shallow water tables, and nearby groundwater use. In addition, it should be noted that assessing the effectiveness of BMPs at removing constituent concentrations is itself subject to uncertainties because of inconsistencies in study methods (such as sample collection and constituent analysis) and reporting protocols (Strecker et al 2001). **Table 3** summarizes the comparative removal effectiveness of various BMPs.

## 2.5 Conditions for Groundwater Recharge

Groundwater originates, in part, from the infiltration and percolation of surface water through the soil matrix. There are a number of variables that determine whether conditions are suitable for groundwater recharge using urban runoff in a given location. First, the ability of surface water to reach groundwater depends on a number of factors, including: 1) permeability of surface soil and the subsurface soil matrix, 2) antecedent soil moisture, 3) soil properties such as texture, organic content, porosity and hydraulic conductivity (which in turn determine rates of infiltration and percolation), 4) depth to groundwater, and 5) the volume of water available for infiltrating to an aquifer (Dunne and Leopold 1979, Novotny and Olem 1994, Urbonas and Stahre 1993). Secondly, water moves through the soil under gravitational forces, displacing water stored previously until it eventually reaches the saturated zone. Successive storms that keep this soil layer moist provide a greater opportunity for this stored water to reach groundwater. If, however, the soil layer is dry, percolation rates will decrease because the capillary forces holding water in the soil are stronger than the gravitational forces that tend to drive moisture further down (Dunne and Leopold 1979). Small storms may not produce a sufficient volume of runoff to infiltrate beyond the root zone before the soil begins to dry out again. Finely textured soils, such as clays (which have expanding properties when exposed to water), have lower infiltration rates and may require less intense but longer duration storms to achieve sufficiently deep percolation to reach groundwater. The various factors that affect infiltration make it difficult to calculate whether runoff from a given storm event will actually reach groundwater sources. Under some circumstances, it may be that only the infrequent, large storm events will generate sufficient volumes of surface water to reach groundwater, and only with sufficient antecedent moisture.

**Table 1**
**Removal Efficiency of Stormwater BMPs**

| BMP Types | Suspended Sediment | Phosphorous | Nitrogen | Oxygen Demand | Metals | Bacteria |
|---|---|---|---|---|---|---|
| Bio-retention | High | Moderate | Moderate | Mod Low | Moderate to Mod High | Mod Low |
| Catch basin inserts | Mod High | Low | Low | Low | Mod High (those designed for metals) | Low |
| Extended detention basin | High | Moderate | Mod Low | Moderate | Mod High | Low |
| Grass swale | Moderate to Mod High | Mod Low | Mod Low | Mod Low | Mod Low | Unknown |
| Infiltration basin | High | Moderate | Moderate | Mod High | High | Mod High |
| Media filtration | Mod High to High | Mod Low[1] | Mod Low[1] | Unknown | Mod High | Low |
| Porous pavement | High | Moderate | Mod High | Mod High | High | High |
| Retention basin | Mod High | Moderate | Moderate | Unknown | Mod High | Moderate |
| Wetland or wet pond | High | Mod High | Moderate | Mod Low | Mod High | Mod High |

**KEY:**
High 80-100% Removal
Mod High 60-80% Removal
Moderate 40-60% Removal
Mod Low 20-40% Removal
Low 0-20% Removal

Source: Glick, 1998, Schueler, 1987, USEPA, 1999
[1] Removal efficiency is high if organic media used

While infiltration can be an important component of stormwater management, there are a number of caveats that must be factored in when planning a recharge facility. According to the USGS, ideal conditions for groundwater recharge are rare, thus a well developed set of guidelines offers the best strategy for determining the suitability of a recharge operation. Pretreatment of stormwater to remove suspended solids significantly reduces clogging of the surface soil, and periodic cleaning is required to maintain infiltration rates. The presence of faults or folds and clay lenses below the surface can inhibit recharge by directing infiltrating water away from the targeted area (USGS 2004).

Sites where the groundwater table is less than ten feet below the infiltration bed or where very sandy soils and low organic content exist are least suitable for groundwater recharge unless runoff is first treated to remove pollutants (Urbonas and Stahre 1993). Too much infiltration in areas of shallow groundwater could also create conditions for liquefaction. Liquefaction is caused by creating a shallow water table in poorly consolidated geologic materials, which can results in unstable soils particularly when shaken by an earthquake (USGS 2004). As previously discussed, some constituents are more mobile under certain conditions. Pitt et al (1996) recommend that in the following cases runoff should be diverted or treated:

- Dry-weather storm drainage effluent should be diverted or pretreated due to potentially high concentrations of pathogens, soluble heavy metals and pesticides;
- Combined sewage overflows should be diverted because of poor water quality;
- Runoff from manufacturing industrial areas should be diverted or pretreated because of potentially high concentrations of soluble toxicants;
- Construction site runoff should either be diverted or treated prior to release for infiltration due to high concentrations of suspended solids which can quickly clog infiltration beds; and
- Runoff from vehicle service stations and other critical source areas should be pretreated to minimize or eliminate groundwater contamination from petroleum hydrocarbons.

## 2.6 Summary

The most significant impacts on groundwater quality in urban environments come from leaking or leaching of contaminants from underground storage tanks, septic systems, landfills, or previously contaminated soil in industrial areas (WEF 1998). In general, concentrations of constituents in urban runoff are many orders of magnitude more dilute than pure product or other historical pollution sources (WEF 1998). This review indicates that infiltration of stormwater has not been found to pose considerable risk to groundwater contamination, given appropriate soil characteristics, depth to aquifers, pretreatment of problematic substances, diversion of runoff from select sources, knowledge of geological formations that may inhibit effective infiltration, and proper design and maintenance of infiltration facilities. Some urban runoff pollutants, such as nitrates and viruses, may have the potential to reach groundwater under certain conditions. The use of BMPs for pretreatment of stormwater greatly reduces the potential risk of groundwater contamination.

There is also the potential to increase soil contamination as a result of pollutant accumulation in the top layers of soil, which may present long-term disposal planning issues in some situations. Individual site conditions should be assessed to determine this. While the ability of soils to continue to filter and adsorb constituents is not precisely known, some researchers estimate that it could take upwards of 200 years to exhaust soil capacity in particular locations (Cox and Livingston 1997, Mikkelson et al 1996, Pitt et al 1996, WEF 1998).

While it is clear that numerous caveats must be considered when urban runoff is being investigated for recharge of potable groundwater, it is also important to note that groundwater recharge offers a number of benefits to municipal water managers. Groundwater storage is less costly in terms of construction costs, environmental impacts, evaporation loss of water, and eutrophication as compared to surface-water reservoirs (USGS 2004). Further, recharging groundwater puts the resource in closer proximity to the end-user than pumping water from reservoirs, an additional cost savings. With proper planning and research, the use of urban runoff for recharge of groundwater offers a viable alternative to relying solely on purchased water for such activities, water that may not be available in present quantities for purchase in the future.

# 3. PROJECT STUDY PLAN

The objective of the monitoring program was to evaluate the potential effects of infiltrating urban stormwater runoff on groundwater quality, via engineered infiltration systems referred to as Best Management Practices (BMPs). During the Phase I Pilot Study, two sites were monitored in the Los Angeles area. The monitoring plan included installation of monitoring wells and lysimeters, baseline soil and groundwater sampling, and subsequent monitoring of stormwater runoff and infiltration associated with storm events during the 2001-2002 season. Because the winter season was dry, most of the data collected was baseline groundwater data; only one storm event was sampled.

The Phase II work plan called for adding at least three new monitoring locations – residential, commercial and industrial – and retrofitting the properties with infiltration BMPs and subsurface monitoring equipment. Soil samples were collected during installation of the monitoring equipment, to characterize constituent concentrations prior to infiltration. For each winter between 2002 and 2005, several storm events were monitored, including the first storm of each season. Subsurface monitoring followed each sampled storm event.

## 3.1 Monitoring Sites

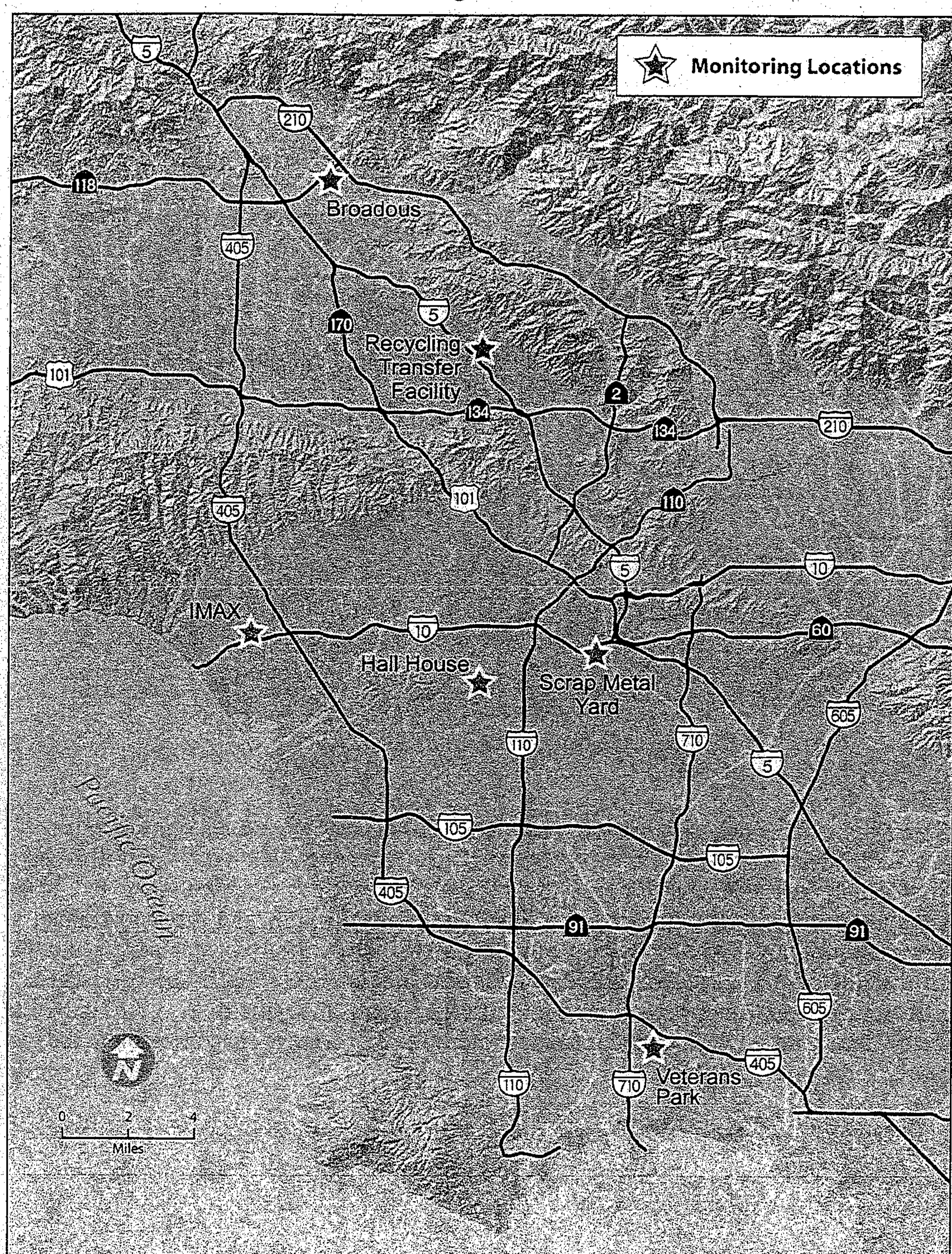
Three locations were monitored during 2002-2003 winter. Six locations were monitored during the 2003-2004 and 2004-2005 seasons (**Figure 2**). Two of these sites, the Broadous Elementary School and IMAX Corporation, were established during the Phase I Pilot Study. A residential location was added to the program in 2002. Three additional monitoring locations were added prior to the 2003-2004 rainy season: two industrial and one commercial/recreational site. Geomatrix Consultants designed and constructed BMPs and installed monitoring equipment at the three new sites. Each of the monitoring sites is described briefly in the following sections. For the industrial sites, which are privately owned, only a generic name and location are provided.

### 3.1.1 Broadous Elementary School

The Broadous Elementary School (Broadous) is located in Pacoima, a neighborhood within the city of Los Angeles. The BMP for the seven acre site consists of a runoff collection system, sedimentation tank, and subsurface infiltration system installed in 2001 in the playground area of the school (Figure 3)

Runoff samples are collected from one sample point in the playground area near the inlet to the BMP. The original lysimeter was installed adjacent to the infiltration BMP, 25 feet downgradient and at a depth of 60 feet. Prior to the 2003-2004 rainy season, a new lysimeter was installed at the edge of the infiltration system, at a depth of 24 feet, to better characterize water quality exiting the BMP.

Figure 2
Monitoring Site Locations



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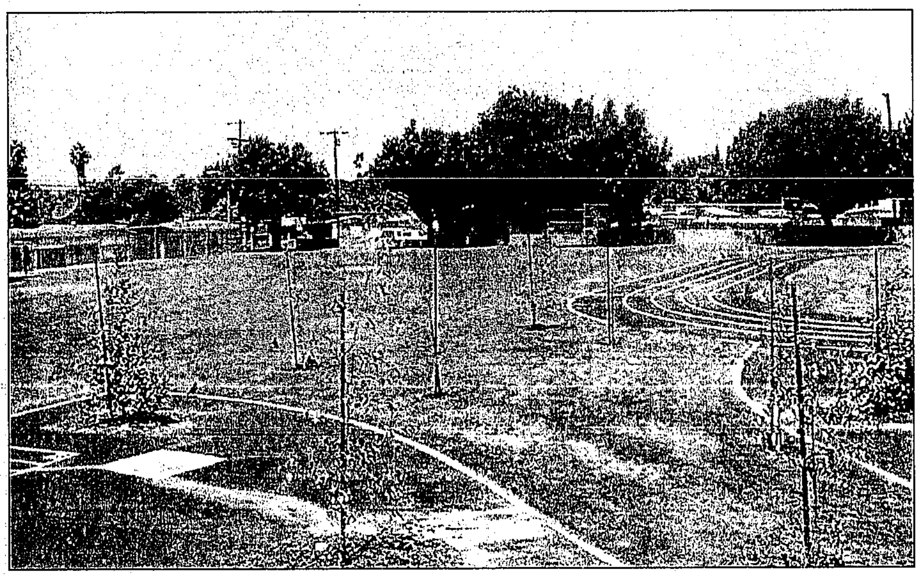
There are also two groundwater monitoring wells at the site, one upgradient and one downgradient of the infiltration BMP. In January of 2003, soil moisture sensors were installed downgradient of the infiltration system, at depths of 25, 35, 45 and 55 feet below the ground surface. These sensors track infiltration rates in the vadose zone throughout the year and were used to estimate timing of subsurface sampling.

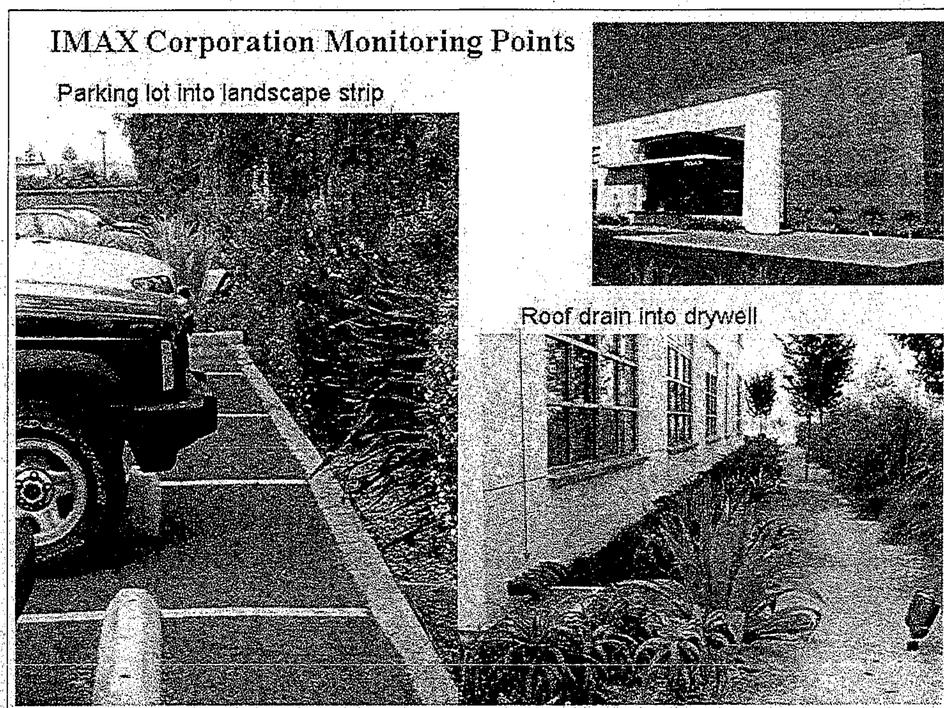
**Figure 3**
**Broadous School Monitoring Site**



### 3.1.2 IMAX Corporation

The IMAX office building is a commercial office facility located in Santa Monica. The 3.5 acre site is equipped with two types of BMPs that are monitored: a drywell receiving roof runoff and a landscaped area that receives parking lot runoff (**Figure 4**). Runoff samples were collected from the front parking lot as it drains into the landscaping, and from the roof downspout at the rear of the building. There are lysimeters adjacent to each of the BMPs, and upgradient and downgradient groundwater wells at the site. There are also four soil moisture sensors in the landscaped area, at depths of 2, 5, 10 and 20 feet below the surface, which track infiltration rates after storm events and throughout the year.

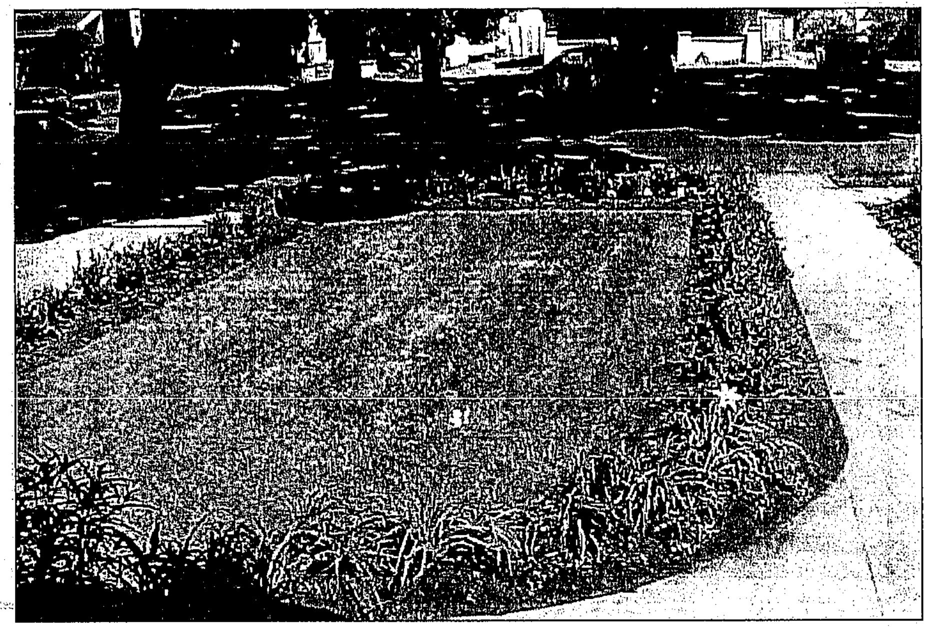
Figure 4
IMAX Monitoring Site




### 3.1.3 Residential Monitoring Site

The Hall residence (Hall House) is located in south Los Angeles. The Hall House is an ongoing demonstration project of TreePeople, and was retrofitted seven years ago with a number of BMPs to contain runoff on site. The front lawn of the Hall House serves as a swale to collect runoff from the roof (**Figure 5**) and also has a drywell that collects runoff conveyed from a trench drain in the driveway. A lysimeter is installed at the edge of the lawn nearest the roof drain. Runoff samples are collected from the roof drain and the driveway. Local groundwater is at a depth of approximately 200 feet below the ground surface. Because of the site configuration in relation to the direction of groundwater flow, there is no groundwater monitoring well installed at this site.

Figure 5
Hall House Front Lawn



### 3.1.4 Metal Recycler

The Metal Recycler is an industrial site located at the southern edge of downtown Los Angeles (**Figure 6**). Facility operations include recycling of bulk ferrous and non-ferrous metals and appliances. The infiltration BMP at this site was designed to intercept runoff from a 0.85 acre portion of the site, pretreat the collected stormwater to reduce the concentrations of sediment, oil and grease, and infiltrate the treated stormwater. The stormwater treatment system consists of a concrete detention/sedimentation basin that receives site runoff and discharges into a subsurface infiltration gallery through a modified standpipe designed to perform limited runoff pretreatment.

Stormwater samples were collected from two locations at this site, representing influent to and effluent from the stormwater treatment device. The four lysimeters are installed adjacent to the infiltration gallery, at depths ranging from 20 to 52 feet. The monitoring well is downgradient of the infiltration gallery. This well was also used for geophysical logging to collect conductivity data that may indicate the path of the wetting front after a storm.

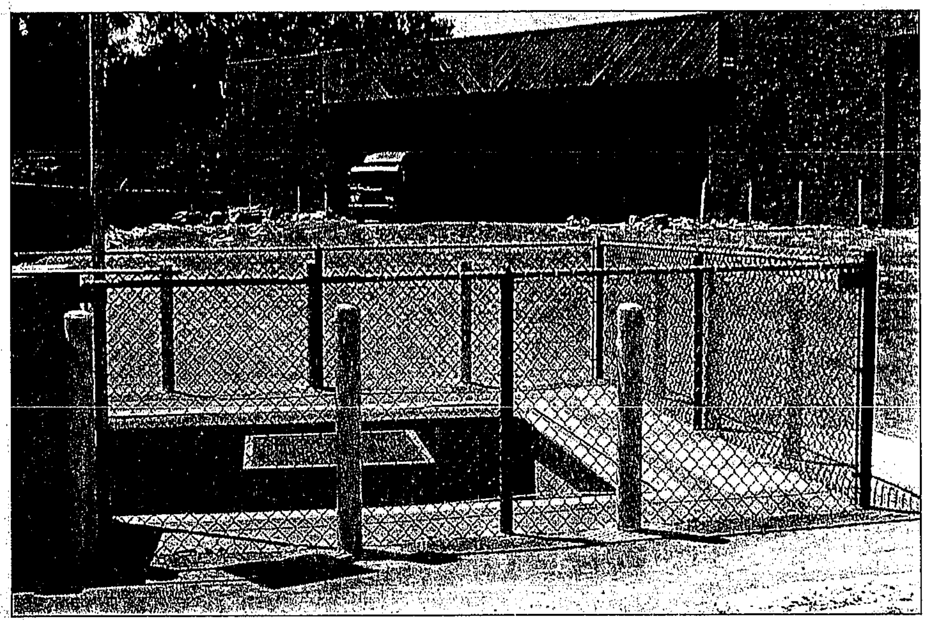
Figure 6
Metal Recycler Detention Basin

### 3.1.5 Recycling Facility

The recycling facility is an industrial facility located in Sun Valley, a neighborhood of the city of Los Angeles (**Figure 7**). Operations at the site consist of receiving and sorting materials for recycling: paper, glass, plastics and metal containers. The infiltration BMP at the Sun Valley site was designed to intercept runoff from a 2.3 acre portion of the paved yard. The stormwater treatment system is similar to that at the Metal Recycler, consisting of a concrete detention/settling basin which discharges into a subsurface infiltration gallery through a modified standpipe designed to perform some pretreatment. Runoff from a portion of the roof is directed to the same underground infiltration gallery via separate buried piping, however it does not undergo pretreatment.

Sample collection points at the site consist of three stormwater sample collection locations, five vadose zone lysimeters and one monitoring well installed in the vadose zone for geophysical logging. No groundwater monitoring wells have been installed at this site however there is an existing downgradient well off-site that was sampled periodically. Stormwater samples were collected from roof runoff, from the yard area entering the sedimentation basin prior to treatment, and from the pipe that directs stormwater from the basin to the infiltration trench. The lysimeters are installed in pairs near the infiltration area at depths ranging from 22 to 71 feet. The monitoring well is competed to a depth of approximately 143 feet. Groundwater is estimated to occur at about 350 feet below the surface.

Figure 7
Sun Valley Recycling Facility Detention Basin



### 3.1.6 Veterans Park

Veterans Park is located in west Long Beach. The site is a public park operated by the City of Long Beach (**Figure 8**). The infiltration BMP at Veterans Park was designed to intercept runoff from a 0.5 acre portion of the site (a parking lot and adjoining sidewalks), treat the collected stormwater to reduce the concentrations of sediment and oil and grease, and infiltrate the treated stormwater. Stormwater collection for the BMP system consists of catch basins positioned to intercept surface flow along existing flow lines at the eastern and western edges of the parking lot. The discharge pipelines from the catch basins direct stormwater to a buried, concrete sand/oil interceptor, then to an underground infiltration gallery.

Stormwater samples are collected from surface flow entering the two catch basins located in the parking lot. The two lysimeters are located adjacent to the infiltration area. Four groundwater monitoring wells are located both upgradient and downgradient of the infiltration gallery.

Details for the infiltration BMPs and monitoring points at each location are provided in **Table 2** and **Table 3**.

Figure 8
Veterans Park Parking Lot

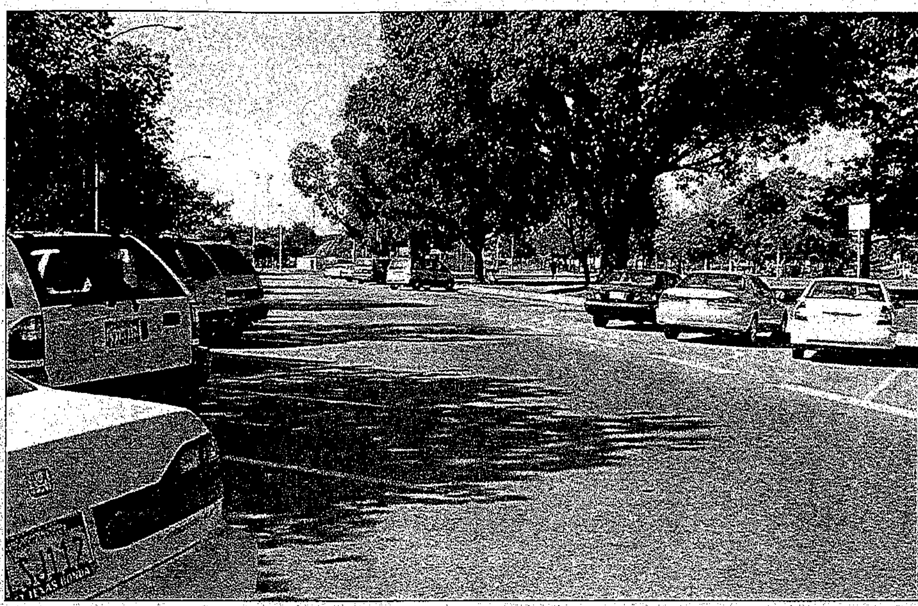


Table 2
Monitoring Sites BMP Hydrology

| Parameter | Units | Broadous | IMAX | Hall House | Metal Recycler | Veterans Park | Sun Valley |
|---|---|---|---|---|---|---|---|
| Sample Point | | Paved school yard | 1) Roof 2) Parking lot | 1) Roof 2) Driveway | Paved Yard | Parking lot | 1) Roof 2) Paved Yard |
| Design Rainfall | inches | 0.75 | 0.75 | 10 | 0.75 | 0.75 | 0.75 |
| Design Storm Intensity (max) | in/hr | 0.75 | 0.75 | 100-year event | 0.75 | 0.75 | 0.75 |
| Catchment Area (est) | sq. ft. | 305,000 | 1) 47,916 2) 68,390 | 3,000 | 37,200 | 21,200 | 1) 51,000 2) 75,000 |
| Runoff Volume | gallons | 95,200 | N/A | N/A | 17,400 | 9,900 | 1) 23,850 2) 35,065 |
| Design Runoff Rate | gal/min | N/A | N/A | N/A | 286 | 165 | 1) 394 2) 580 |
| BMP Inlet | | Sheet flow direct to pretreatment separator | 1) roof drain to dry well 2) Sheet flow into landscape strip | 1) Roof drain to landscaping 2) Sheet flow to driveway drain | Sheet flow direct to sedimentation basin | Sheet flow to catch basin; pipes to buried sedimentation vault | 1) Roof drain direct to buried perforated pipes 2) Sheet flow direct to sedimentation basin |

| Parameter | Units | Broadous | IMAX | Hall House | Metal Recycler | Veterans Park | Sun Valley |
|---|---|---|---|---|---|---|---|
| Sediment Removal | | Yes | No | Yes | Yes | Yes | 1) No<br>2) Yes |
| Oil/Grease Removal | | Yes | No | Yes | Yes | No | 1) No<br>2) Yes |
| Recharge Method | | Buried infiltration units in gravel bed | Direct through soil | Buried dry well | Buried perforated pipeline in gravel bed | Buried perforated pipeline in gravel bed | Buried perforated pipeline in gravel bed |

N/A: data not available

## Table 3
## Monitoring Points

| Site Date Completed | Surface Water Monitoring Point ID | Collection Point | Lysimeter ID | Installed Depth (ft) | Monitoring Well ID | Initial Groundwater Depth |
|---|---|---|---|---|---|---|
| Broadous | B-SW-01 | School Yard | B-LS-02 | 24 | B-MW-01 | 155 feet |
| | | | | | B-MW-02 | 139 feet |
| IMAX | I-SW-01 | Roof Drain | I-LS-01 | 8 | I-MW-01 | 32 feet |
| | I-SW-02 | Parking Lot | I-LS-03 | 10 | I-MW-02 | 31 feet |
| Hall House | H-SW-01 | Roof Drain | H-LS-01 | 8 | none | |
| | H-SW-02 | Driveway | | | | |
| Veterans Park | V-SW-01 | Parking Lot | V-LS-01 | 15 | V-MW-01 | 23 feet |
| | V-SW-02 | Roof Drain | V-LS-02 | 15 | V-MW-02 | 23 feet |
| | | | | | V-WM-03 | 23 feet |
| | | | | | V-MW-04 | 22 feet |
| Metal Recycler | M-SW-01 | Detention Basin Inlet | M-LS-01 | 37 | M-MW-01 | 225 feet |
| | M-SW-02 | Detention Basin Outlet | M-LS-02 | 51 | | |
| | | | M-LS-03 | 37 | | |
| | | | M-LS-04 | 51 | | |
| | | | | | | |
| Sun Valley | S-SW-01 | Roof Drain | S-LS-01 | 25 | S-MW-01 | 143 feet |
| | S-SW-02 | Detention Basin Inlet | S-LS-02 | 47 | | Installed casing to run geophysical logs. (groundwater depth is ~350 feet below surface) |
| | S-SW-03 | Detention Basin Outlet | S-LS-03 | 25 | | |
| | | | S-LS-04 | 47 | | |
| | | | S-LS-05 | 71 | | |

## 3.2 Sampling Program Scope

Surface water sampling occurred during rain events, with subsurface sampling following. The goal was to sample at least two storm events at each monitoring site each year.

### 3.2.1 Mobilization Criteria

Sampling crews were mobilized only if a predicted storm was likely to produce sufficient runoff for sample collection and no significant rainfall occurred within 48 hours prior. To assess the mobilization criteria professional weather consultants, Weather Watch in San Diego and Meteorological Solutions (through Los Angeles County Pubic Works), were consulted to provide more comprehensive weather data than is commonly available through the Internet. Services included long- and short-range forecasts via their websites, email updates, and telephone consultation available near the onset of a storm. For pending storm events, estimates of total rainfall and probability of predicted rainfall were provided in 3-hour increments.

### 3.2.2 Subsurface Sampling Schedule

After each storm, lysimeter samples were collected from all sites. The volume of each lysimeter is typically less than required for the full suite of analytes, therefore when necessary sampling was conducted over a two or three day period. All sites except Hall House and Sun Valley have on-site monitoring wells. Wells at sites with relatively shallow groundwater were sampled in response to monitored storms (just after the collection of lysimeter samples), and wells at sites with relatively deep groundwater were sampled periodically throughout the storm season.

Induction logs are collected at the two sites with the deepest underlying groundwater, the Metal Recycler and Sun Valley. The intent was that these logs would distinguish zones of percolating stormwater (high conductivity wet soil) from other regions of the subsurface (low conductivity dry soil). Soil moisture data is also continuously recorded from sensors installed in 2003 at IMAX and Broadous. These data are periodically downloaded from the dataloggers at each site.

### 3.2.3 Sampling Procedures

During the 2001-2002 and 2002-2003 monitoring seasons, runoff samples were discrete grab samples collected during the early portion of the runoff event. During the 2003-2004 and 2004-2005 monitoring seasons, runoff samples were collected manually as time-weighted composite samples at twenty minute increments, with volatile organics and bacteria collected as grab samples. At the Metal Recycler and Sun Valley sites, automated samplers were used during the 2003-2004 season to collect whole storm flow-weighted composite samples, but due to equipment difficulties these were not reinstalled the next season. The flow-weighted composite samples are useful for estimating EMCs. The grab samples and two-hour time-weighted composites are likely more representative of the "first flush" concentration which may be higher than EMC for many constituents. All



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water samples were submitted for analysis to Calscience Environmental Laboratories, Inc. in Garden Grove, California, within a few hours of collection.

### 3.2.4 Analytical Suite

The analytical suite is presented in **Table 4.** Additionally, temperature, pH and conductivity were measured in the field. Not all constituents were analyzed from lysimeter samples, for several reasons. Sampling from the lysimeters is restricted by the amount of water that can be evacuated from a lysimeter, which varies according to soil moisture conditions. Additionally, some analytes, such as total suspended solids and turbidity, are not measurable in a lysimeter, as they would be filtered by the lysimeter itself. Therefore, the sampling suite for lysimeters was reduced to selected priority analytes. A detailed list of constituents, including detection limits and laboratory methods, is provided in **Appendix B.**

Some constituents have consistently resulted in non-detects at all sample points. Bacteriological constituents (total coliforms, E. coli, and fecal coliforms) occur in stormwater, sometimes in very high concentrations, but detections in the lysimeter and groundwater samples have been extremely low or not detected at all. At the end of each season, the TAC revisited the constituent list to eliminate some of these constituents for the next season. For example, NDMA, pesticides, 1,4-Dioxane and bacteriological constituents were dropped from the list for the oldest sites after two years, and for the newest sites after one round of samples. Fuel oxygenates, in addition to MtBE, were added to the organics analysis (DIPE, ETBE, TAME, TBA and ethanol). The detection limit for 1,2,3-trichloropropane, an emerging contaminant in groundwater, was reduced to 0.005 µg/L for one round of samples at all sites.

**Table 4**
**Summary of Analytical Suite**

| Category | Stormwater and wells | Lysimeters |
|---|---|---|
| General Minerals | X | X |
| Trace Metals (total & dissolved) | X | X |
| Oil and Grease | X | Hall House |
| Perchlorate | X | X |
| Glyphosate | X | Vets Park |
| Volatile organic compounds (VOCs) | X | X |
| Semi-volatile organic compounds (SVOCs) | X | |
| NDMA | X | |
| Surfactants | X | |
| Bacteria (total coliform, fecal coliform, e. coli) | X | X |

### 3.2.5 Quality Control

In order to ensure the validity of sample results, a number of laboratory quality control procedures were followed, in accordance with our state-approved Quality Assurance Project Plan. The Quality Assurance Program Plan (QAPP) addresses field sample collection procedures, sample tracking and handling, and laboratory quality assurance and quality control (QA/QC) requirements. The laboratory selected for this project, Calscience Environmental Laboratories, is a certified laboratory with extensive experience with stormwater sampling requirements and a full range of analytical capabilities.

#### *3.2.5.1 Field Quality Assurance/Quality Control*

Field QA/QC samples were collected periodically and used to evaluate potential contamination and sampling error occurring prior to sample delivery to the analytical laboratory, and to verify laboratory results. Field QA/QC samples include trip blanks, equipment blanks, field blanks, and field duplicates.

Blank samples help verify that the equipment and the sample containers are not a source of contamination, and that the sampling techniques used are non-contaminating. Duplicates are used to assess variability attributable to shipment, storage, and/or laboratory handling and analysis. Procedures for collecting field blanks and duplicates are the same as that used for collecting the field samples.

#### *3.2.5.2 Laboratory Quality Assurance/Quality Control*

Analytical quality assurance/quality control for this study included the following:

- Employing analytical chemists trained in the procedures to be followed.
- Adherence to documented procedures, EPA methods, written Standard Operating Procedures, and other approved Standard Methods.
- Calibration of analytical instruments.
- Complete documentation of sample tracking and analysis.
- Internal laboratory quality control checks through the analysis of method blanks, MS/MSDs, lab duplicates, and lab control samples.

The last point references additional sample analysis that is performed routinely by the lab. Method blanks are run by the laboratory for each sample batch to determine the level of contamination, if any, associated with laboratory reagents and equipment. MS/MSDs, lab duplicates and lab control samples/duplicates are also run routinely for each batch, as sample volume is available and when samples are collected specifically for this purpose. Duplicate analyses results are evaluated by calculating the relative percent difference between the two sets of results. This serves as a measure of the reproducibility (precision) of the sample results.

#### *3.2.5.3 Data Quality Objectives*

Data quality objectives (DQOs) are quantitative and qualitative statements that clarify study objectives, and specify the tolerable levels of potential errors in the data. As defined in the Quality Assurance Project Plan, DQOs specify the quantity and quality of data required to support the study objectives. DQOs are generally used to determine the level of error considered to be acceptable in the data produced by the monitoring program. They are also used to specify acceptable ranges of field sampling and laboratory performance. DQOs for accuracy and precision have been achieved overall in the collected QA/QC samples.

Volatile organic compounds (VOCs) are of particular concern for groundwater quality. Because of their volatile nature, VOCs are rarely included in stormwater monitoring programs, so there is little comparative data. Over the course of the study methylene chloride was detected in a number of QC samples corresponding to field detections. These detections are likely the result of laboratory contamination and are flagged as such by the laboratory. In addition, acetone, toluene and 2-butanone (MEK) were detected in at least one field blank collected on the same day at the Broadous School, Hall House, and IMAX sites, as well as in an equipment blank, which may indicate contamination by sampling equipment. Although acetone is used on occasion in the laboratory, it was not present in any trip blanks in cases where it was detected in corresponding field samples, nor was it ever reported in laboratory method blanks. MEK is also often attributed to laboratory contamination however Calscience does not use it in their laboratory.

In one source identification study undertaken by USGS, toluene, acetone and MEK were found in all stormwater samples from a parking lot (Lopes et al 2000). This study also detected acetone and MEK in direct precipitation samples, indicating atmospheric sources. Acetone is an unregulated compound and is common in the environment from solvents, air emissions, and is a by-product of photosynthesis. Acetone was present in most stormwater samples at all sites, but only present in a few lysimeter and groundwater samples.

Dissolved organic carbon (DOC) was also detected in method blanks, indicating interference from the filter material used in sample filtration. When this occurs, reported DOC results are slightly inflated and are flagged as such by the laboratory. Overall, data quality and reliability seemed more than adequate to achieve the goals of the study.

# 4. MONITORING RESULTS

This section presents the results of the monitoring performed during the course of the Phase I and II monitoring program, from 2001 to 2005. Monitoring results include all analytical results from:

- Soil samples from all sites during lysimeter installation (pre-infiltration) and at the end of the monitoring phase.
- Pre- and post-season groundwater samples from upgradient and downgradient wells.
- Stormwater samples at all sites.
- Lysimeter samples from all sites.
- Post-storm groundwater samples from downgradient wells

A schedule of storm events sampled for each monitoring site is provided in **Table 5**. Additional sampling dates for limited lysimeter sampling, and baseline and end of season groundwater sampling are reflected in the **Appendix C** tables.

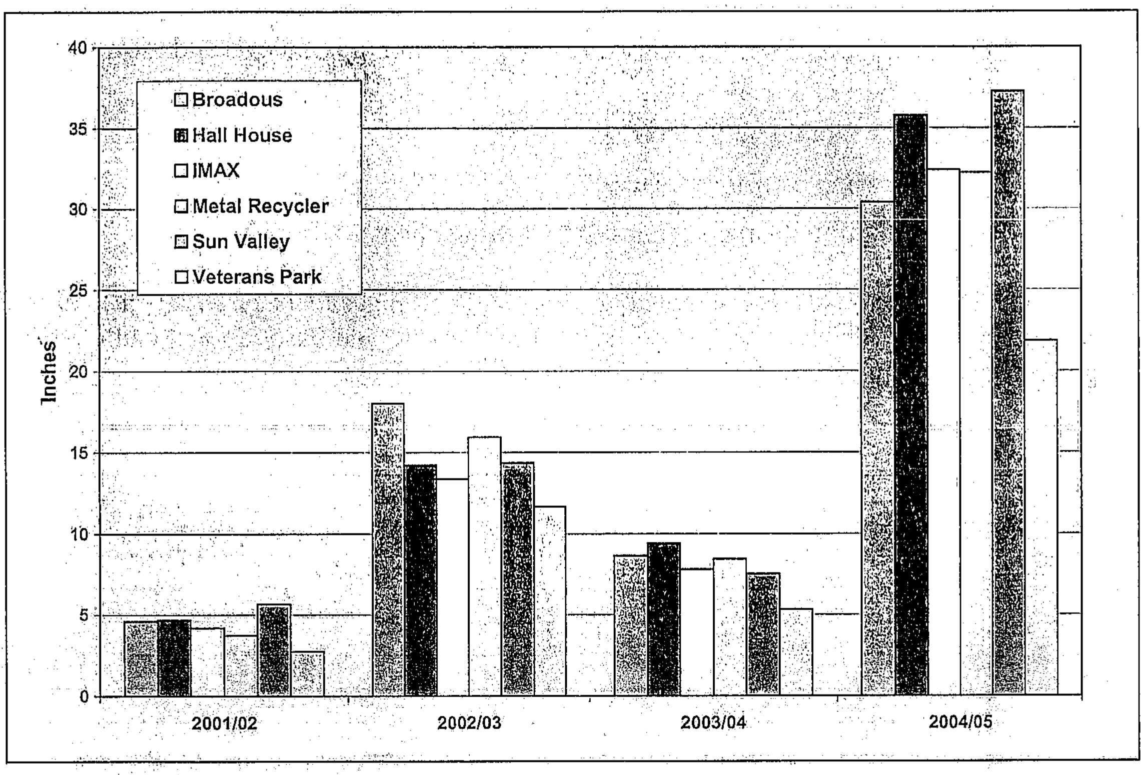
**Table 5**
**Storm Event Sample Collection Dates**

| Event Date | IMAX | Broadous | Hall House | Metal Recycler | Sun Valley | Veterans |
|---|---|---|---|---|---|---|
| 12/03/01 | | X | | | | |
| 11/08/02 | X | X | | | | |
| 12/16/02 | X | X | X | | | |
| 2/12/03 | X | X | X | | | |
| 3/15/03 | X | X | | | | |
| 2/02/04 | X | X | X | X | X | X |
| 2/18/04 | | | | X | X | X |
| 2/25/04 | X | X | X | | | |
| 10/19/04 | | | | | X | X |
| 10/26/04 | | | | X | | |
| 12/27/04 | X | X | | X | X | X |
| 1/07/05 | | | X | | | |
| 2/11/05 | | | | X | X | X |
| 2/18/05 | X | X | X | | | |
| Total Events | 8 | 9 | 6 | 5 | 5 | 5 |

## 4.1 Description of the Storm Seasons

Annual rainfall for the six monitoring locations is shown in **Figure 9**, measured from the nearest Los Angeles County rain gauge. The four years of monitoring saw a wide range of rainfall variability, from the driest year on record (2001-2002) to the second wettest year on record (2004-2005). Rainfall varied geographically as well during the study. Total rainfall amounts during 2004-05 ranged from about 22 inches at Veterans Park, to over 37 inches at the Sun Valley site (LACDPW 2005). This spatial and temporal variability presents some challenges not just for monitoring, but also for trying to appropriately size infiltration facilities to capture runoff cost-effectively.

**Figure 9**
**Annual Rainfall by Monitoring Site**




## 4.2 Groundwater Conditions

Depth to groundwater was measured whenever groundwater monitoring wells were sampled. Hydrographs depicting the groundwater elevations calculated for the sites are shown in **Appendix I**. Although groundwater elevations in the monitoring wells varied over the term of the study, all wells designated as downgradient were considered to have been subject to potential influence by stormwater infiltrated during the period of the study.

## 4.3 ANALYTICAL RESULTS

This section provides analytical results for all sampling points for selected constituents of concern in groundwater, including: general monitoring parameters (total dissolved solids [TDS], total suspended solids [TSS], nitrate, and chloride), total and dissolved metals (aluminum, arsenic, cadmium, copper, hexavalent chromium, lead, mercury, and zinc), volatile organic compounds (VOCs), semi-volatile compounds (SVOCs), biological constituents (total coliforms, fecal coliform, and E. coli), and other constituents of interest such as perchlorate, NDMA, 1,4-dioxane and glyphosate. Polycyclic aromatic hydrocarbons, or PAHs, were not detected in any sample during the course of this study.

Comprehensive water quality analytical results are presented in **Appendix C**. Concentration ranges (minimum, maximum) of selected constituents discussed in this section are presented in site-specific summary tables (**Tables 6 to 11**) at the end of this section. The summary tables contain ranges of analytical results for selected general monitoring parameters, dissolved metals, biological and other constituents, and any VOCs and SVOCs detected in at least one sample.

For comparison purposes, results from other water quality sampling programs are presented in **Appendix D**. Data from this study were compared to those from the Los Angeles County Public Works' land use monitoring program (LACDPW 2002) and the Southern California Coastal Water Research Project's (SCCWRP) region-wide comparison of constituent loads from different land uses (Ackerman 2003), to assess whether the sites sampled for this study were typical for their land use. The LACDPW data were collected between 1994 and 2000 for compliance with LACDPW's 1996 NPDES stormwater permit, and results are summarized by land use category. Values represent the mean and median of all EMCs, analyzed from flow-weighted composite samples. The constituents included in these two previous studies are similar to those included in the WAS program but not as extensive, for example VOCs and perchlorate were not included. VOCs are not typically sampled in stormwater because of their volatility, and perchlorate has not been identified as a pollutant of concern for stormwater. Although results based on EMCs and composite samples are not directly comparable, the concentrations of general monitoring parameters and metals in stormwater samples collected and analyzed for this study were generally within the range of results reported for similar land use types in the previous studies. Appendix D also includes composite results from recent groundwater samples taken from monitoring wells throughout the West and Central Basins.

### 4.3.1 Broadous School

Monitoring began at this site in October 2001. A summary of sampled storm events is contained in Table 5. Figure A-1 is a site location map showing the installed monitoring and infiltration BMP systems.

Surface stormwater samples were collected at one location in the playground (B-SW-01). At the beginning of the 2003-2004 monitoring season, the location of B-SW-01 was changed in an attempt to collect samples more representative of stormwater runoff that is infiltrated. During the 2001-2002 and 2002-2003 monitoring seasons, samples collected at B-SW-01 were single grab samples collected near the beginning of storm runoff. Samples collected from B-SW-01 during the last two monitoring seasons were time-weighted composites of aliquots collected at approximately 30-minute increments during the first two hours storm runoff.

Soil pore fluid samples were collected from a single lysimeter, B-LS-01. At the beginning of the 2003-2004 monitoring season, the original lysimeter was abandoned because of difficulty collecting samples at that depth, and a new lysimeter, B-LS-02, was installed in a position closer to the infiltration BMP. Pore fluid samples were typically collected daily over a two or three day period beginning one day after collection of a stormwater sample.

Groundwater samples were collected from two monitoring wells, B-MW-01 (upgradient) and B-MW-02 (downgradient). Because groundwater at the site is relatively deep (greater than 130 feet below ground surface [bgs]), groundwater samples were collected periodically during the season rather than in direct response to a storm event.

**Appendix H** presents soil boring logs for Broadous School. Soil analytical data for one sample, B-L-D, collected from the lysimeter borehole on August 26, 2001, are contained in Tables E-1 through E-3. The depth of sample B-L-D was 32 feet below ground surface. The boring logs indicate that the upper 35 feet of sediment at this site is composed of relatively uniform silty sands with some gravel. The soil chemical analytical results indicate VOCs were not detected. Perchlorate was reported at 330 ug/kg, but concentrations of other salts and metals were within the expected ranges for these constituents.

### 4.3.2 Hall House

Monitoring began at this site in December 2002. A summary of sampled storm events is contained in Table 5. Figure A-2 is a site location map showing the installed monitoring and infiltration BMP systems.

Surface stormwater samples were collected at two locations, the roof drain (H-SW-01) and the driveway (H-SW-02). During the 2002-2003 monitoring season, samples collected at the two monitoring stations were single grab samples collected near the beginning of storm runoff. Samples collected during the 2003-2004 and 2004-2005 monitoring seasons were time-weighted composites of aliquots collected at approximately 30-minute increments during the first two hours of storm runoff.

Soil pore fluid samples were collected from a single lysimeter, H-LS-01. Pore fluid samples were typically collected daily over a two or three day period beginning one day after collection of a stormwater sample.

No monitoring wells are installed at the Hall House site.

**Appendix H** presents soil boring logs collected at the Hall House site. Soil analytical data for samples HA-1 and HA-2, collected at depths of 1 and 8 feet bgs on October 28, 2002, and sample H-B-1, collected at a depth of 8 feet bgs on March 10, 2005, are contained in Tables E-1 through E-3. The boring logs indicate that the upper 6 feet of sediment is composed of silt with minor amounts (<10%) of sands and clay. Between 6 and 8 feet bgs some gravel and nonplastic clay were encountered. The soil chemical analytical results did not indicate detected VOCs. Concentrations of salts (nitrate, chloride, sulfate) and some metals (arsenic, lead) were near the lower end of the ranges expected for these constituents, especially considering the fine-grained fraction of sediment present in the sampled depth interval.

### 4.3.3 IMAX

Monitoring began at this site in October 2001. A summary of sampled storm events is contained in Table 5. Figure A-3 is a site location map showing the installed monitoring and infiltration BMP systems.

Surface stormwater samples were collected at two locations; a roof drain (I-SW-01) and a station for collecting parking lot runoff as it discharges into a planter area (I-SW-02). During the 2001-2002 and 2002-2003 monitoring seasons, samples collected at the two monitoring stations were single grab samples collected near the beginning of storm runoff. Samples collected from these monitoring stations during the 2003-2004 and 2004-2005 monitoring seasons were time-weighted composites of aliquots collected at approximately 30-minute increments during the first two hours of storm runoff.

For the first two years of the project, soil pore fluid samples were collected from lysimeters I-LS-01 and I-LS-02. During the summer of 2004, lysimeter I-LS-02 was damaged during road construction. At the beginning of the 2004-2005 monitoring season, this lysimeter was replaced with new lysimeter, I-LS-03, installed in the planter area about 20 feet from the original location. Pore fluid samples were typically collected daily over a two or three day period beginning one day after collection of a stormwater sample.

Groundwater samples were collected from two monitoring wells, I-MW-01 (upgradient) and I-MW-02 (downgradient). Both wells were sampled before and after each monitoring season. I-MW-02 was also sampled after each sampled storm event. Upgradient well I-MW-01 was sampled occasionally during each monitoring season, but not after each sampled storm.

**Appendix H** presents soil boring logs for IMAX and soil analytical data for two samples, I-LS-02 collected from the lysimeter borehole 5 feet bgs on October 16, 2001 and soil sample I-B1 collected approximately 8 feet west of I-LS-02 on March 10, 2005, also at 5 feet bgs. The boring logs for I-LS-2 and I–B1 indicate that the upper 5 feet of sediment at this site is composed primarily of plastic clays and silt with minor amounts (<5%) of sand. The soil chemical analytical results did not indicate detected VOCs. Concentrations of salts (nitrogen, nitrate, chloride, sulfate) and some metals (arsenic, chromium) were reported at relatively high concentration relative to other soil samples tested. Perchlorate was also reported in the sample collected in 2001 but was not detected in the sample from March 2005.

### 4.3.4 Metal Recycler

Monitoring began on this site in November 2003. A summary of sampled storm events is contained in Table 5. Figure A-4 is a site location map showing the installed monitoring and infiltration BMP systems.

Surface stormwater samples were collected at two locations, one collecting runoff from a paved work yard as it enters a catch basin (M-SW-01) and the other sampling the same runoff after pre-treatment (M-SW-02). During the 2003-2004 monitoring season, flow-weighted composite samples were collected using automated equipment. Automated sampling was discontinued because of difficulties using this equipment, and during the 2004-2005 monitoring season samples collected from these monitoring stations were time-weighted composites of aliquots collected at approximately 30-minute increments during the first two hours of storm runoff.

Soil pore fluid samples were collected from four lysimeters, M-LS-01, M-LS-02, M-LS-03, and M-LS-04. Pore fluid samples were typically collected daily over a two or three day period beginning one day after collection of a stormwater sample.

Groundwater samples were collected from one monitoring well, M-MW-01. Groundwater samples were collected at the beginning and end of each monitoring season. Because groundwater at the site is relatively deep (greater than 200 feet bgs), groundwater samples during each monitoring season were collected periodically during the season rather than in direct response to a storm event.

**Appendix H** presents soil boring logs for the Metal Recycler and soil analytical data for two soil samples, M-LS-01 and M-LS-02 collected at 20 and 36.5 feet bgs, respectively, on November 11, 2003. The boring logs indicate that the upper 50 feet of sediment is composed of relatively uniform (poorly graded) silty fine sands. The soil chemical analytical results did not report detected VOCs or perchlorate. However, some of the soil-gas samples collected during the site assessment contained tetrachloroethylene (PCE) and trichloro-fluoromethane. Concentrations of salts and metals (arsenic, chromium) were relatively low compared to those in soil samples from the other sites.

### 4.3.5 Sun Valley

Monitoring began at this site in October 2003. A summary of sampled storm events is contained in Table 5. Figure A-5 is a site location map showing the installed monitoring and infiltration BMP systems.

Surface stormwater samples were collected at three locations, representing roof runoff (S-SW-01), runoff from the paved yard into a collection basin (S-SW-02), and flow discharging from the collection basin after treatment (S-SW-03). During the 2003-2004 monitoring season, flow-weighted composite samples were collected using automated equipment. Automated sampling was discontinued because of difficulties using this equipment, and during the 2004-2005 monitoring season samples collected from these monitoring stations were time-weighted composites of aliquots collected at approximately 30-minute increments during the first two hours storm runoff.

Soil pore fluid samples were collected from five lysimeters, S-LS-01, S-LS-02, S-LS-03, S-LS-04, and S-LS-05. Pore fluid samples were typically daily collected over a two or three day period beginning one day after collection of a stormwater sample.

Groundwater beneath the site occurs at more than 300 feet bgs and no on-site monitoring wells were installed. As an indication of regional groundwater quality, samples were collected from EV-10, an inactive groundwater supply well owned by the Los Angeles Department of Water and Power and located about a mile downgradient from the site. Groundwater samples were collected from EV-10 at the beginning and ending of each monitoring season.

**Appendix H** presents soil boring logs collected at the Sun Valley site. Soil analytical data is presented in Tables E1 through E3. Five soil samples collected at this site were analyzed: S-1 (collected at 5 feet bgs on October 29, 2003), S-LS-01 and S-LS-02, (collected at 23 and 46 feet bgs, respectively, on November 11, 2003), and S-B-01-1 and S-B-01-2 (collected at 23 and 46 feet bgs, respectively, on March 17, 2005). The boring logs indicate that the upper 50 feet of sediment is composed of relatively uniform (poorly graded) sand with gravel. The soil chemical analytical results did not indicate detected VOCs or perchlorate. Concentrations of salts and metals (arsenic, chromium, nickel, zinc) were low compared to those in soil samples from the other sites.

### 4.3.6 Veterans Park

Monitoring began on this site in November 2003. A summary of sampled storm events is contained in Table 5. Figure A-6 is a site location map showing the installed monitoring and infiltration BMP systems.

Surface stormwater samples are collected at two locations where runoff enters parking lot catch basins (V-SW-01 and V-SW-02). Samples collected from these monitoring stations were time-weighted composites of aliquots collected at approximately 30-minute increments during the first two hours storm runoff.

Soil pore fluid samples were collected from two lysimeters, V-LS-01 and V-LS-02. Pore fluid samples were typically daily collected over a two or three day period beginning one day after collection of a stormwater sample.

Groundwater samples were collected from four monitoring wells. V-MW-01 is downgradient to crossgradient and is more than 100 feet from the infiltration gallery. The other three wells are within about 30 feet of the infiltration gallery: V-MW-02 (relatively upgradient), V-MW-03 (relatively upgradient), and V-MW-04 (relatively downgradient). All wells were sampled before and after each monitoring season. V-MW-04 was also sampled after each sampled storm event. The other three wells were sampled occasionally during each monitoring season, but not after each sampled storm.

**Appendix H** presents soil boring logs for Veterans Park and soil analytical data for two samples, V-LS-1 and V-B1, collected at 10 to 15 feet bgs on October 29, 2003 and March 11, 2005, respectively. The boring logs indicate that the upper 10 feet of sediment is composed of interbedded silts and fine sands. The soil chemical analytical results did not indicate detected VOCs or perchlorate. Concentrations of salts (alkalinity, calcium, potassium, chloride and sulfate) were variable, as were metals concentrations (barium, chromium, copper and zinc).

## Table 6 Summary Results – Broadous

| Constituent | Units[1] | Fraction | Monitoring Station[2] | | | | |
|---|---|---|---|---|---|---|---|
| | | | B-SW-01 | B-LS-01 | B-LS-02 | B-MW-01 | B-MW-02 |
| **General Monitoring Parameters** | | | | | | | |
| Nitrate (as N) | mg/L | N/A | ND - 1 | 0.583 - 110 | 2.4 - 4 | 0.3 - 8.4 | 5.6 - 10.509 |
| Total Kjeldahl Nitrogen | mg/L | N/A | 1.1 - 6.2 | -- | ND | ND - 0.34 | ND - 0.35 |
| Ammonia-Nitrogen | mg/L | N/A | ND - 1.02 | ND - 0.14 | ND - 0.35 | ND | ND - 0.33 |
| Total Dissolved Solids | mg/L | N/A | 43 - 330 | 78 – 1700 | 490 - 990 | 540 - 680 | 570 - 846 |
| Total Suspended Solids | mg/L | N/A | 12 - 200 | 130 | -- | ND - 2548 | ND - 2100 |
| Chemical Oxygen Demand | mg/L | N/A | 23 - 220 | 247 | ND - 36 | ND - 32.37 | ND - 120 |
| Chloride | mg/L | N/A | 2 - 72 | 70-160 | 37 - 130 | 22-87 | 19-28.28 |
| **Metals** | | | | | | | |
| Aluminum | µg/L | Dissolved | ND - 259 | ND | ND | ND | ND |
| Aluminum | µg/L | Total | 337 - 6500 | ND - 68.7 | ND | ND - 176 | ND - 17900 |
| Arsenic | µg/L | Dissolved | ND - 2.5 | 2.18 - 5.63 | 1.91 - 11.3 | ND | ND - 1.29 |
| Arsenic | µg/L | Total | ND - 2.99 | ND - 7.92 | 2.2 - 12.3 | ND - 3.5 | ND - 2.86 |
| Cadmium | µg/L | Dissolved | ND | ND | ND - 0.215 | ND | ND |
| Chromium, Hexavalent | µg/L | Dissolved | ND - 0.49 | 0.39 – 0.59 | 0.62 - 1.2 | 0.1 - 1.7 | ND - 1.1 |
| Copper | µg/L | Dissolved | ND - 22.1 | 5.83 - 66.9 | 2.68 - 19 | ND - 5.27 | ND - 87 |
| Copper | µg/L | Total | 4.33 - 39.9 | 10.3 - 220 | 2.85 - 19 | ND - 73.1 | ND - 87 |
| Lead | µg/L | Dissolved | ND - 1.22 | ND - 0.54 | ND - 0.695 | ND | ND - 9.56 |
| Lead | µg/L | Total | ND - 36.3 | ND - 6.44 | ND - 0.84 | ND - 34.7 | ND - 30.4 |
| Mercury | µg/L | Dissolved | ND | -- | ND | ND | ND - 0.109 |
| Zinc | µg/L | Dissolved | 7.54 - 369 | 42.2 - 828 | 6.91 - 71.8 | ND - 412 | ND - 77.5 |
| Zinc | µg/L | Total | 14.1 - 369 | ND - 2060 | 11.1 - 25.9 | 5.69 - 950 | ND - 157 |
| **Other Constituents** | | | | | | | |
| MBAS (Surfactants) | mg/L | N/A | ND - 0.38 | -- | -- | ND | ND |
| Oil and Grease | µg/L | N/A | ND - 3.6 | -- | -- | ND - 1.3 | 1.6 - 2.9 |
| Perchlorate | µg/L | N/A | ND - 5.2 | ND | ND | ND | ND |

| | | | Monitoring Station[2] | | | | |
|---|---|---|---|---|---|---|---|
| Constituent | Units[1] | Fraction | B-SW-01 | B-LS-01 | B-LS-02 | B-MW-01 | B-MW-02 |
| **Volatile Organic Compounds** | | | | | | | |
| Benzene | µg/L | N/A | ND | ND | ND | ND - 2.3 | ND - 0.87 |
| Toluene | µg/L | N/A | ND | ND | ND | ND - 6.4 | ND |
| Ethylbenzene | µg/L | N/A | ND | ND | ND | ND - 1.2 | ND - 1.1 |
| o-Xylene | µg/L | N/A | ND | ND | ND | ND - 8.4 | ND - 3.2 |
| p/m-Xylene | µg/L | N/A | ND | ND | ND | ND - 5.7 | ND - 3.8 |
| Tetrachloroethylene (PCE) | µg/L | N/A | ND | ND | ND | ND - 44 | ND - 1.5 |
| 1,2,4-Trimethylbenzene | µg/L | N/A | ND | ND | ND | ND - 1.1 | ND - 1 |
| 1,3,5-Trimethylbenzene | µg/L | N/A | ND | ND | ND | ND - 1.1 | ND - 0.55 |
| 2-Butanone (Methylethyl ketone) | µg/L | N/A | ND - 8.8 | ND | ND | ND - 1 | ND - 1 |
| Acetone | µg/L | N/A | ND - 37 | ND | ND - 600 | ND - 26 | ND - 2.7 |
| Carbon disulfide | µg/L | N/A | ND | ND - 5.6 | ND – 2.5 | ND | ND |
| Diethyl Ether | µg/L | N/A | ND - 0.8 | ND | ND | ND | ND |
| Naphthalene | µg/L | N/A | ND | ND | ND | ND - 1.1 | ND - 1.1 |
| Tert-Butyl Alcohol (TBA) | µg/L | N/A | ND | ND - 12 | ND | ND | ND |
| **Semi-Volatile Organic Compounds** | | | | | | | |
| Bis(2-Ethylhexyl) Phthalate | µg/L | N/A | ND - 20 | -- | -- | ND - 4.8 | ND - 74.3 |
| **Biological Parameters** | | | | | | | |
| Total Coliforms | MPN/100 mL | N/A | 1300 - 35000 | ND - 90000 | -- | 12 - 30000 | ND - 11000 |
| Fecal Coliform | MPN/100 mL | N/A | 80 - 5000 | ND | -- | 23 | ND - 1.1 |
| E. coli | MPN/100 mL | N/A | 20 - 1300 | ND | -- | 6.9 | ND |
| | | | | | | | |

1. Units of measure: mg/L = milligrams per liter, µg/L = micrograms per liter, MPN/100 mL = most probable number per 100 milliliters.
2. "--" indicates the constituent was not analyzed for. Analytes not detected are indicated by ND.

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## Table 7 Summary Results – Hall House

| | | | Monitoring Station[2] | | |
|---|---|---|---|---|---|
| Constituent | Units[1] | Fraction | H-SW-01 | H-SW-02 | H-LS-01 |
| **General Monitoring Parameters** | | | | | |
| Nitrate (as N) | mg/L | N/A | ND - 0.39 | 0.24 - 1.5 | ND - 0.28 |
| Total Kjeldahl Nitrogen | mg/L | N/A | ND - 2 | 1.4 - 24 | ND - 0.28 |
| Ammonia-Nitrogen | mg/L | N/A | ND - 0.49 | 0.28 - 2 | ND |
| Total Dissolved Solids | mg/L | N/A | 10 - 82 | 28 - 48 | 290 - 610 |
| Total Suspended Solids | mg/L | N/A | ND - 51 | 9.6 - 110 | -- |
| Chemical Oxygen Demand | mg/L | N/A | 5 - 74 | 69 - 280 | ND - 5.1 |
| Chloride | mg/L | N/A | ND-3.2 | ND-3.4 | ND-65 |
| **Metals** | | | | | |
| Aluminum | µg/L | Dissolved | ND | ND - 122 | ND |
| Aluminum | µg/L | Total | ND - 2540 | 1340 - 8210 | ND |
| Arsenic | µg/L | Dissolved | ND | ND - 1.19 | ND - 4.26 |
| Arsenic | µg/L | Total | ND - 1.31 | ND - 3.56 | ND |
| Cadmium | µg/L | Dissolved | ND - 0.396 | ND | ND - 0.245 |
| Chromium, Hexavalent | µg/L | Dissolved | ND - 0.41 | ND - 0.95 | 0.37 - 0.66 |
| Copper | µg/L | Dissolved | 1.3 - 6.93 | 3.81 - 17 | 1.58 - 7.71 |
| Copper | µg/L | Total | 1.55 - 41.3 | 28.8 - 123 | 2.43 - 6.4 |
| Lead | µg/L | Dissolved | 1.86 - 6.16 | 0.522 - 3.12 | ND - 0.591 |
| Lead | µg/L | Total | 8.81 - 99.3 | 46 - 138 | ND - 0.598 |
| Mercury | µg/L | Dissolved | ND | ND | ND |
| Zinc | µg/L | Dissolved | 86.3 - 496 | 27.4 - 88.1 | ND - 56.9 |
| Zinc | µg/L | Total | 93.4 - 933 | 189 - 849 | 6.36 - 38.3 |
| **Other Constituents** | | | | | |
| MBAS (Surfactants) | mg/L | N/A | ND - 0.37 | ND - 0.36 | -- |
| Oil and Grease | µg/L | N/A | ND - 2.2 | 1.6 - 52 | ND - 1.1 |
| **Volatile Organic Compounds** | | | | | |
| 2-Butanone (Methylethyl ketone) | µg/L | N/A | ND | ND - 1.8 | ND |
| Acetone | µg/L | N/A | 7.9 - 26 | 6.6 - 15 | ND |
| Carbon disulfide | µg/L | N/A | ND | ND | ND - 3.6 |
| Tert-Butyl Alcohol (TBA) | µg/L | N/A | ND | ND | ND - 12 |
| **Semi-Volatile Organic Compounds** | | | | | |
| Bis(2-Ethylhexyl) Phthalate | µg/L | N/A | ND | 400 | -- |
| **Biological Parameters** | | | | | |
| Total Coliforms | MPN/100 mL | N/A | ND - 600 | -- | -- |
| Fecal Coliform | MPN/100 mL | N/A | ND | -- | -- |
| E. coli | MPN/100 mL | N/A | ND | -- | -- |

1. Units of measure: mg/L = milligrams per liter, µg/L = micrograms per liter, MPN/100 mL = most probable number per 100 milliliters.
2. "--" indicates the constituent was not analyzed for. Analytes not detected are indicated by ND.

## Table 8 Summary Results – IMAX

| | | | Monitoring Station[2] | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Constituent | Units[1] | Fraction | I-SW-01 | I-SW-02 | I-LS-01 | I-LS-02 | I-LS-03 | I-MW-01 | I-MW-02 |
| **General Monitoring Parameters** | | | | | | | | | |
| Nitrate (as N) | mg/L | N/A | 0.15 - 0.44 | ND - 1.2 | 7.7 - 320 | 0.41 - 8.2 | 0.41 - 1 | 3.2 - 16 | 7.2 - 24.365 |
| Total Kjeldahl Nitrogen | mg/L | N/A | ND - 1.5 | 0.84 - 2.1 | ND - 0.46 | ND | ND | ND - 1 | ND - 0.42 |
| Ammonia-Nitrogen | mg/L | N/A | ND - 0.35 | ND - 0.56 | ND - 0.056 | ND - 0.063 | ND | ND - 0.337 | ND |
| Total Dissolved Solids | mg/L | N/A | 6.7 - 34 | 6.7 - 37 | 710 - 3000 | 130 - 750 | 180 - 750 | 630 - 840 | 500 - 882 |
| Total Suspended Solids | mg/L | N/A | ND - 110 | ND - 140 | -- | -- | -- | 7.1 - 130 | ND - 1667 |
| Chemical Oxygen Demand | mg/L | N/A | 7.7 - 64 | 13 - 61 | ND - 58 | 6 - 36 | 5.1 - 20 | ND - 7.6 | ND - 131.6 |
| Chloride | mg/L | N/A | ND-1.8 | ND-3.6 | 53-120 | ND-94 | ND - 94 | 22-60 | 29-50 |
| **Metals** | | | | | | | | | |
| Aluminum | µg/L | Dissolved | ND | ND - 105 | ND | ND | ND | ND | ND |
| Aluminum | µg/L | Total | ND - 1180 | 105 - 952 | ND - 455 | 124 - 455 | ND | 8.8 - 3680 | ND - 495 |
| Arsenic | µg/L | Dissolved | ND | 1.3 - 138 | 1.62 - 6.78 | 2.2 - 22.1 | 3.17 - 4.77 | ND - 1.4 | ND - 2 |
| Arsenic | µg/L | Total | ND - 6.51 | 1.44 - 153 | 1.51 - 8.47 | 9.74 - 28.6 | 3.15 - 5.39 | ND - 4.3 | ND - 5.15 |
| Cadmium | µg/L | Dissolved | ND | ND | ND - 0.524 | ND | ND | ND | ND |
| Chromium, Hexavalent | µg/L | Dissolved | ND - 0.3 | ND - 0.61 | 2 - 35.2 | 0.55 - 74 | 0.55 - 1 | 5.6 - 24 | ND - 4.6 |
| Copper | µg/L | Dissolved | 1.17 - 8.2 | 1.99 - 137 | ND - 10.1 | ND - 4.48 | ND - 1.32 | ND - 5.22 | ND - 38.5 |
| Copper | µg/L | Total | 2.51 - 37.7 | 4.99 - 157 | 3.65 - 25.5 | 3.01 - 34 | ND - 1.26 | ND - 20.8 | ND - 47.3 |
| Lead | µg/L | Dissolved | ND | ND - 0.769 | ND - 0.866 | ND | ND | ND | ND - 0.816 |
| Lead | µg/L | Total | ND - 76.4 | 0.947 - 13.7 | ND - 6.3 | 0.723 - 9.4 | ND | ND - 3 | ND - 11.2 |
| Mercury | µg/L | Dissolved | ND | ND | -- | ND | ND | ND | ND - 0.154 |
| Zinc | µg/L | Dissolved | 37.7 - 169 | 32.5 - 757 | 25 - 130 | 21 - 4650 | 6.89 - 9.07 | ND - 75.3 | ND - 400 |
| Zinc | µg/L | Total | 60.6 - 566 | 50.3 - 1240 | 62.8 - 209 | 120 - 7050 | 8.5 - 14.2 | ND - 80.1 | ND - 400 |
| **Other Constituents** | | | | | | | | | |
| MBAS (Surfactants) | mg/L | N/A | ND - 0.19 | ND - 0.19 | -- | -- | -- | ND - 0.19 | ND - 0.15 |
| Oil and Grease | µg/L | N/A | ND - 58 | ND - 1.7 | -- | -- | -- | ND - 1 | 1.7 |
| Perchlorate | µg/L | N/A | ND - 14 | ND | ND | ND | -- | ND - 8.2 | ND - 15 |

| Constituent | Units[1] | Fraction | Monitoring Station[2] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | I-SW-01 | I-SW-02 | I-LS-01 | I-LS-02 | I-LS-03 | I-MW-01 | I-MW-02 |
| **Volatile Organic Compounds** | | | | | | | | | |
| Methyl-t-Butyl Ether (MtBE) | µg/L | N/A | ND | ND | ND | ND | ND | ND | ND - 1.3 |
| Benzene | µg/L | N/A | ND | ND | ND | ND | ND | ND - 3.1 | ND - 2.6 |
| Toluene | µg/L | N/A | ND | ND | ND | ND | ND | ND - 2.4 | ND - 16 |
| Ethylbenzene | µg/L | N/A | ND | ND | ND | ND - 27 | 16 - 27 | ND - 2.1 | ND - 9.3 |
| o-Xylene | µg/L | N/A | ND | ND | ND | ND - 37 | 33 - 37 | ND - 5.6 | ND - 19 |
| p/m-Xylene | µg/L | N/A | ND | ND | ND | ND - 170 | 89 - 170 | ND - 6.7 | ND - 33 |
| Tetrachloroethylene (PCE) | µg/L | N/A | ND | ND | ND | ND | ND | ND - 0.73 | ND - 38 |
| 1,2,4-Trimethylbenzene | µg/L | N/A | ND | ND | ND | ND - 2.1 | 1.2 - 2.1 | ND - 1.9 | ND - 6.9 |
| 1,3,5-Trimethylbenzene | µg/L | N/A | ND | ND | ND | ND - 0.6 | ND - 0.6 | ND - 0.81 | ND - 3 |
| 2-Butanone (Methylethyl ketone) | µg/L | N/A | ND - 1.5 | ND - 1.7 | ND | ND | ND | ND | ND |
| Acetone | µg/L | N/A | 2.5 - 17 | 2.6 - 15 | ND - 3.7 | ND - 2.1 | ND - 2.1 | ND - 2.7 | ND - 3.1 |
| Carbon disulfide | µg/L | N/A | ND | ND | ND - 1.2 | ND - 24 | 1.4 - 24 | ND | ND |
| Diethyl Ether | µg/L | N/A | ND - 0.88 | ND - 1.2 | ND | ND | ND | ND | ND |
| Naphthalene | µg/L | N/A | ND | ND | ND | ND | ND | ND - 2.1 | ND - 1.6 |
| n-Propylbenzene | µg/L | N/A | ND | ND | ND | ND | ND | ND | ND - 0.75 |
| Tert-Butyl Alcohol (TBA) | µg/L | N/A | ND | ND | ND - 13 | ND | ND | ND | ND |
| **Semi-Volatile Organic Compounds** | | | | | | | | | |
| Bis(2-Ethylhexyl) Phthalate | µg/L | N/A | ND | ND | -- | -- | -- | ND | ND - 202.3 |
| Phenol | µg/L | N/A | ND | ND | -- | -- | -- | ND | ND - 18 |
| **Biological Parameters** | | | | | | | | | |
| Total Coliforms | MPN/100 mL | N/A | 500 | ND - 13000 | ND - 8 | ND - 13 | -- | ND - 800 | 11 - 110 |
| Fecal Coliform | MPN/100 mL | N/A | 20 | ND - 260 | ND | ND | -- | ND | ND |
| E. coli | MPN/100 mL | N/A | 20 | ND - 120 | ND | ND | -- | ND | ND |

1. Units of measure: mg/L = milligrams per liter, µg/L = micrograms per liter, MPN/100 mL = most probable number per 100 milliliters.
2. "--" indicates the constituent was not analyzed for. Analytes not detected are indicated by ND.

## Table 9 Summary Results - Metal Recycler

| | | | Monitoring Station[2] | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Constituent | Units[1] | Fraction | M-SW-01 | M-SW-02 | M-LS-01 | M-LS-02 | M-LS-03 | M-LS-04 | M-MW-01 |
| **General Monitoring Parameters** | | | | | | | | | |
| Nitrate (as N) | mg/L | N/A | 1.6 - 4.2 | 3.2 - 4.2 | 1 - 16 | 1 - 5.6 | ND - 3.8 | 5.7 - 12 | ND - 0.12 |
| Total Kjeldahl Nitrogen | mg/L | N/A | 6.4 - 11 | 8.3 - 9.5 | ND - 2.7 | ND - 1.4 | 0.98 - 1.3 | 2.1 - 2.5 | ND - 1.1 |
| Ammonia-Nitrogen | mg/L | N/A | 0.84 - 1.9 | 0.91 - 2.5 | ND - 2.1 | ND - 0.28 | ND | ND - 0.7 | ND |
| Total Dissolved Solids | mg/L | N/A | 520 - 1400 | 670 - 1400 | 570 - 1700 | 630 - 1300 | 1100 - 1200 | 820 - 1100 | 840 - 1100 |
| Total Suspended Solids | mg/L | N/A | 61 - 1200 | 100 - 1200 | -- | -- | -- | -- | ND - 20 |
| Chemical Oxygen Demand | mg/L | N/A | 570 - 3400 | 420 - 2100 | 13 - 54 | 18 - 46 | 33 - 79 | 84 - 240 | ND - 57 |
| Chloride | mg/L | N/A | 35-100 | 50-72 | 28-110 | 35-99 | 60-110 | 36-79 | 70-86 |
| **Metals** | | | | | | | | | |
| Aluminum | µg/L | Dissolved | ND - 248 | ND - 379 | ND | ND | ND | ND | ND |
| Aluminum | µg/L | Total | 434 - 8360 | 868 - 5620 | ND | ND | ND | ND | ND - 330 |
| Arsenic | µg/L | Dissolved | ND - 2.96 | ND - 2.94 | ND - 5.14 | ND - 3.1 | 3.32 - 13.9 | 2.88 - 5.67 | 0.765 - 5.65 |
| Arsenic | µg/L | Total | 1.72 - 11.9 | 4.16 - 10.3 | ND - 4.02 | 0.992 - 2.98 | 8.52 - 13.5 | 2.77 - 5.44 | 1.83 - 8.39 |
| Cadmium | µg/L | Dissolved | 0.627 - 3.26 | 0.285 - 14.1 | 0.294 - 0.761 | ND - 0.637 | ND | ND - 0.27 | ND |
| Chromium, Hexavalent | µg/L | Dissolved | 6.3 - 74 | ND - 52 | ND - 1.9 | ND - 4.2 | ND - 0.6 | 6 - 14 | ND - 0.23 |
| Copper | µg/L | Dissolved | 59.7 - 158 | 47 - 153 | 3.01 - 17.4 | 3.33 - 6.99 | 2.93 - 6.54 | 7.36 - 16.5 | ND - 1.41 |
| Copper | µg/L | Total | 148 - 792 | 124 - 330 | 3.58 - 27.2 | 4.17 - 14.6 | 3.08 - 6.69 | 8.74 - 17.3 | ND - 3.46 |
| Lead | µg/L | Dissolved | 11.8 - 120 | 3.69 - 185 | ND - 6.82 | ND - 0.632 | ND - 1.62 | ND - 0.95 | ND |
| Lead | µg/L | Total | 292 - 3020 | 460 - 1560 | 1.33 - 6.9 | 0.872 - 4.23 | ND - 0.785 | ND - 0.61 | ND - 1.16 |

| | | | Monitoring Station[2] | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Constituent | Units[1] | Fraction | M-SW-01 | M-SW-02 | M-LS-01 | M-LS-02 | M-LS-03 | M-LS-04 | M-MW-01 |
| Mercury | µg/L | Dissolved | ND - 0.235 | ND - 0.279 | ND | ND | ND | ND | ND - 0.103 |
| Zinc | µg/L | Dissolved | 16.9 - 244 | 26.6 - 1550 | 35.7 - 101 | 20.6 - 165 | 19.5 - 26.3 | 21.2 - 27.2 | ND - 14 |
| Zinc | µg/L | Total | 957 - 3220 | 1170 - 2790 | 64 - 141 | 18.5 - 195 | 12.2 - 27.2 | 11.4 - 45 | ND - 17.3 |
| **Other Constituents** | | | | | | | | | |
| MBAS (Surfactants) | mg/L | N/A | 0.48 - 1.7 | 0.86 - 1.7 | -- | -- | -- | -- | ND |
| Oil and Grease | µg/L | N/A | 49 - 390 | 17 - 170 | -- | -- | -- | -- | ND - 2.4 |
| Perchlorate | µg/L | N/A | ND - 120 | ND - 170 | 13 - 140 | 15 - 54 | ND - 33 | 10 - 18 | ND |
| **Volatile Organic Compounds** | | | | | | | | | |
| Methyl-t-Butyl Ether (MtBE) | µg/L | N/A | ND - 1.3 | ND - 1.7 | ND - 33 | ND - 26 | ND - 10 | ND - 2.9 | ND |
| Benzene | µg/L | N/A | ND - 0.83 | ND - 2.3 | ND - 0.65 | ND - 2.3 | ND - 0.7 | ND | ND |
| Toluene | µg/L | N/A | ND - 5.8 | ND - 25 | ND - 13 | ND - 5.8 | ND - 3 | ND | ND |
| Ethylbenzene | µg/L | N/A | ND - 2 | ND - 7.1 | ND - 4.3 | ND - 0.7 | ND - 0.93 | ND | ND |
| o-Xylene | µg/L | N/A | ND - 3.8 | ND - 11 | ND - 8.1 | ND - 1.5 | ND - 2.9 | ND | ND |
| p/m-Xylene | µg/L | N/A | ND - 8.6 | ND - 28 | ND - 19 | ND - 2.7 | ND - 3.7 | ND | ND |
| Tetrachloroethylene (PCE) | µg/L | N/A | ND | ND | ND - 0.92 | ND | 0.51 - 1.1 | ND | ND |
| 1,2,4-Trimethylbenzene | µg/L | N/A | ND - 4.3 | ND - 10 | ND - 4 | ND | ND - 0.83 | ND | ND |
| 1,3,5-Trimethylbenzene | µg/L | N/A | ND - 1.1 | ND - 2.8 | ND - 1.3 | ND | ND | ND | ND |
| 2-Butanone (Methylethyl ketone) | µg/L | N/A | 5.2 - 14 | 5.4 - 32 | ND | ND - 11 | ND - 1.3 | ND | ND |
| 4-Methyl-2-pentanone (MIBK) | µg/L | N/A | ND | ND - 21 | ND | ND | ND - 10 | ND | ND |
| Acetone | µg/L | N/A | 20 - 79 | 19 - 190 | ND - 4.4 | ND - 34 | ND - 37 | ND - 16 | ND |
| Carbon disulfide | µg/L | N/A | ND | ND | ND - 6.9 | ND - 3.5 | ND - 2 | ND - 0.57 | ND - 1.7 |
| Dichlorodifluoromethane | µg/L | N/A | ND - 4.1 | ND - 3.8 | ND | ND | ND | ND | ND |
| Diethyl Ether | µg/L | N/A | ND | ND - 1.1 | ND | ND - 1.7 | ND | ND | ND |
| Ethanol | µg/L | N/A | 160 - 1200 | 120 - 22000 | ND | ND - 3200 | ND | ND | ND |
| Methyl Methacrylate | µg/L | N/A | ND - 3.9 | ND - 3.1 | ND - 2.3 | ND | ND | ND | ND |

| | | | Monitoring Station[2] | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Constituent** | **Units[1]** | **Fraction** | **M-SW-01** | **M-SW-02** | **M-LS-01** | **M-LS-02** | **M-LS-03** | **M-LS-04** | **M-MW-01** |
| Naphthalene | µg/L | N/A | ND - 1.7 | 0.51 - 8.6 | ND | ND | ND | ND | ND |
| n-Propylbenzene | µg/L | N/A | ND | ND - 1.1 | ND - 0.69 | ND | ND | ND | ND |
| Styrene | µg/L | N/A | ND - 1.3 | ND - 7.2 | ND - 1.5 | ND | ND | ND | ND |
| Tert-Butyl Alcohol (TBA) | µg/L | N/A | ND - 15 | ND - 22 | ND - 11 | ND - 17 | ND - 24 | ND | ND |
| Tetrahydrofuran | µg/L | N/A | ND | ND - 11 | ND | ND | ND - 3.6 | ND | ND |
| Trichlorofluoromethane | µg/L | N/A | ND -4.2 | ND - 28 | ND - 1 | ND - 1.8 | ND - 1.4 | ND - 0.7 | ND |
| **Semi-Volatile Organic Compounds** | | | | | | | | | |
| 4-Methylphenol (p-Cresol) | µg/L | N/A | ND | ND - 24 | -- | -- | -- | -- | ND |
| 4-Nitrophenol | µg/L | N/A | ND | ND - 19 | -- | -- | -- | -- | ND |
| Benzoic acid | µg/L | N/A | ND -770 | ND - 560 | -- | -- | -- | -- | ND |
| Benzyl alcohol | µg/L | N/A | ND | ND - 40 | -- | -- | -- | -- | ND |
| Bis(2-Ethylhexyl) Phthalate | µg/L | N/A | ND | 23 - 26 | -- | -- | -- | -- | ND |
| Butyl Benzyl Phthalate | µg/L | N/A | ND | ND - 11 | -- | -- | -- | -- | ND |
| Phenol | µg/L | N/A | ND | ND - 62 | -- | -- | -- | -- | ND |
| **Biological Parameters** | | | | | | | | | |
| Total Coliforms | MPN/100 mL | N/A | 2400 | 270 | 20 | ND | ND | ND | ND |
| Fecal Coliform | MPN/100 mL | N/A | 230 | 40 | ND | ND | ND | ND | ND |
| E. coli | MPN/100 mL | N/A | 310 | 10 | ND | ND | ND | ND | ND |
| | | | | | | | | | |

1. Units of measure: mg/L = milligrams per liter, µg/L = micrograms per liter, MPN/100 mL = most probable number per 100 milliliters.
2. "--" indicates the constituent was not analyzed for. Analytes not detected are indicated by ND.



A005582

## Table 10 Summary Results - Sun Valley

| Constituent | Units[1] | Fraction | Monitoring Station[2] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | S-SW-01 | S-SW-02 | S-SW-03 | S-LS-01 | S-LS-02 | S-LS-03 | S-LS-04 | S-LS-05 | EV-10 |
| **General Monitoring Parameters** | | | | | | | | | | | |
| Nitrate (as N) | mg/L | N/A | ND - 0.62 | ND - 0.63 | ND - 1.8 | 2.2 - 15 | 1 - 17 | 1.9 - 17 | 0.43 - 36 | ND - 0.77 | 1.7 - 2.1 |
| Total Kjeldahl Nitrogen | mg/L | N/A | 0.7 - 3.6 | 1.4 - 11 | 1.5 - 13 | ND - 1.4 | ND - 0.84 | ND - 1.1 | ND - 0.56 | 0.98 - 6.7 | ND - 0.14 |
| Ammonia-Nitrogen | mg/L | N/A | ND - 0.35 | 0.21 - 1.8 | 0.28 - 1.2 | ND - 0.56 | ND | ND | ND - 0.28 | ND - 0.28 | ND |
| Total Dissolved Solids | mg/L | N/A | 44 - 94 | 48 - 420 | 76 - 460 | 340 - 920 | 720 - 2200 | 350 - 1000 | 310 - 1300 | 810 - 4500 | 420 - 430 |
| Total Suspended Solids | mg/L | N/A | 9.5 - 290 | 41 - 930 | 31 - 780 | -- | -- | -- | -- | -- | 1.5 - 14 |
| Chemical Oxygen Demand | mg/L | N/A | 13 - 170 | 48 - 730 | 71 - 900 | ND - 53 | ND - 20 | ND - 35 | ND - 15 | 13 - 51 | 5 - 5.1 |
| Chloride | mg/L | N/A | ND-2.7 | ND-21 | 3.5-18 | 10-28 | 13-38 | 12-30 | 8.1-35 | 34-81 | 25-26 |
| **Metals** | | | | | | | | | | | |
| Aluminum | µg/L | Dissolved | ND | ND - 97.3 | ND - 198 | ND | ND | ND | ND | ND | ND |
| Aluminum | µg/L | Total | 84.5 - 2530 | 514 - 3660 | 406 - 6570 | ND | ND - 50.3 | ND | ND | ND | ND |
| Arsenic | µg/L | Dissolved | ND - 1.05 | ND - 11.6 | 1.1 - 9.93 | 4.63 - 15.7 | 4.82 - 11.4 | ND - 5.16 | 2.16 - 6.97 | 3.17 - 31.2 | ND - 0.879 |
| Arsenic | µg/L | Total | ND - 1.65 | 0.809 - 13.9 | 1.44 - 13 | 4.38 - 13.3 | 4.58 - 13.4 | ND - 6.65 | 1.84 - 7.79 | 3.12 - 30.6 | ND - 0.849 |
| Cadmium | µg/L | Dissolved | ND - 0.244 | ND - 0.764 | ND - 0.614 | ND - 0.272 | ND - 0.501 | ND | ND - 0.23 | 0.2 - 0.586 | ND |
| Chromium, Hexavalent | µg/L | Dissolved | ND - 0.48 | ND - 0.98 | 0.37 - 1.3 | 0.43 - 6.2 | ND - 31 | 12 - 26 | 1.3 - 5.5 | ND - 1 | 0.23 - 0.26 |
| Copper | µg/L | Dissolved | 6.54 - 13.5 | 7.35 - 43.7 | 11.3 - 23.3 | 1.78 - 8.76 | ND - 7.77 | 1.14 - 7.07 | 2.74 - 41.5 | 2.3 - 5.19 | 1.03 - 1.13 |
| Copper | µg/L | Total | 8.63 - 42.2 | 19.3 - 83.5 | 19.2 - 86.2 | 2.52 - 9.04 | 1.03 - 8.23 | 2.35 - 6.73 | 3.22 - 33.7 | 2.4 - 5.99 | 4 - 5.25 |
| Lead | µg/L | Dissolved | ND - 0.603 | ND - 6.09 | ND - 58.2 | ND - 0.592 | ND | ND - 0.608 | ND - 1.68 | ND - 0.838 | ND |
| Lead | µg/L | Total | 3.66 - 63.6 | 19.4 - 108 | 10.6 - 956 | ND - 5.46 | ND - 0.847 | ND - 1.51 | ND - 1.48 | 0.582 - 3.57 | 0.652 - 1.07 |
| Mercury | µg/L | Dissolved | ND | ND - | ND - | ND | ND | ND | ND | ND | ND |

| Constituent | Units[1] | Fraction | Monitoring Station[2] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | S-SW-01 | S-SW-02 | S-SW-03 | S-LS-01 | S-LS-02 | S-LS-03 | S-LS-04 | S-LS-05 | EV-10 |
| | | | | 0.168 | 0.192 | | | | | | |
| Zinc | µg/L | Dissolved | 23.4 - 74 | 38.5 - 174 | 43.6 - 350 | ND - 17.7 | 9.4 - 31.3 | ND - 18.6 | 18.7 - 49.7 | 7.37 - 28.6 | 14.2 - 61.6 |
| Zinc | µg/L | Total | 98.4 - 284 | 99 - 387 | 83.2 - 669 | ND - 19.8 | 12 - 61.3 | 8.37 - 59.8 | 17.7 - 52.5 | 10.2 - 38.2 | 40.8 - 42.7 |
| **Other Constituents** | | | | | | | | | | | |
| MBAS (Surfactants) | mg/L | N/A | 0.24 - 0.42 | 0.32 - 4.1 | 0.32 - 3.9 | -- | -- | -- | -- | -- | ND |
| Oil and Grease | µg/L | N/A | ND - 5.7 | 2.2 - 48 | 2 - 54 | -- | -- | -- | -- | -- | ND |
| Perchlorate | µg/L | N/A | ND | ND - 6.1 | ND - 6.5 | ND | ND | ND - 7.2 | ND - 2.4 | ND | ND |
| **Volatile Organic Compounds** | | | | | | | | | | | |
| Methyl-t-Butyl Ether (MtBE) | µg/L | N/A | ND | ND | ND | ND | ND - 7.3 | ND | ND - 1.3 | ND | ND |
| Toluene | µg/L | N/A | ND | ND - 0.59 | ND - 11 | ND | ND | ND | ND | ND | ND |
| Trichloroethylene (TCE) | µg/L | N/A | ND | ND | ND | ND | ND | ND | ND | ND | 1.2 |
| Tetrachloroethylene (PCE) | µg/L | N/A | ND | ND | ND | ND | ND | ND | ND | ND | 4.1 - 4.9 |
| 1,1,1-Trichloroethane | µg/L | N/A | ND | ND | ND | 5.4 - 18 | 3.3 - 17 | 5.2 - 18 | 3.7 - 17 | ND - 1.4 | ND |
| 1,1-Dichloroethane | µg/L | N/A | ND | ND | ND | 0.56 - 1.6 | 0.56 - 2.1 | ND - 1.4 | ND - 1.3 | ND | 3.5 - 3.6 |
| 1,1-Dichloroethylene | µg/L | N/A | ND | ND | ND | 0.97 - 3.7 | 0.76 - 4.4 | 1.3 - 4.1 | 1.3 - 4.4 | ND | ND |
| 1,2-Dichloroethane | µg/L | N/A | ND | ND | ND | ND | ND | ND | ND | ND | ND - 6.4 |
| 1,4-Dichlorobenzene | µg/L | N/A | ND | ND - 4.7 | ND - 1.3 | ND | ND | ND | ND | ND | ND |
| 2,2-Dichloropropane | µg/L | N/A | ND | ND | ND | ND | ND | ND - 0.97 | ND | ND | ND |
| 2-Butanone (Methylethyl ketone) | µg/L | N/A | ND - 3.7 | 1.7 - 6.1 | 1 - 12 | ND | ND - 1.2 | ND | ND | ND - 670 | ND |
| 2-Hexanone | µg/L | N/A | ND | ND | ND | ND | ND | ND | ND | ND - 6.5 | ND |
| 4-Methyl-2-pentanone (MIBK) | µg/L | N/A | ND | ND - 7.2 | ND - 64 | ND | ND | ND | ND | ND | ND |
| Acetone | µg/L | N/A | 4 - 40 | 16 - 70 | 12 - 130 | ND - 7.3 | 6.4 - 30 | ND - 4.4 | ND - 5.5 | 56 - 2200 | ND - 2.5 |
| Carbon disulfide | µg/L | N/A | ND | ND | ND | ND - 54 | 1.6 - 10 | ND - 76 | 0.57 - 2.2 | ND - 1.8 | ND |
| Chloroform | µg/L | N/A | ND | ND | ND | ND | ND | ND | ND | ND - 2.1 | ND |
| Dichlorodifluoromethane | µg/L | N/A | ND | ND | ND | ND | ND | ND | ND | ND | 5.1 |

| | | | Monitoring Station[2] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Constituent** | **Units[1]** | **Fraction** | **S-SW-01** | **S-SW-02** | **S-SW-03** | **S-LS-01** | **S-LS-02** | **S-LS-03** | **S-LS-04** | **S-LS-05** | **EV-10** |
| Diethyl Ether | µg/L | N/A | ND | ND - 0.94 | ND - 0.78 | ND | ND | ND | ND | ND | ND |
| Ethanol | µg/L | N/A | ND - 290 | 130 - 1900 | ND - 840 | ND | ND | ND | ND | ND | ND |
| Methyl Chloride | µg/L | N/A | ND - 0.56 | ND | ND | ND | ND | ND | ND | ND | ND |
| Tert-Butyl Alcohol (TBA) | µg/L | N/A | ND | ND | ND | ND - 24 | ND - 23 | ND | ND - 54 | ND | ND |
| Trichlorofluoromethane | µg/L | N/A | ND | ND | ND | ND | ND | ND | ND | ND | 1.1 |
| **Semi-Volatile Organic Compounds** | | | | | | | | | | | |
| 2-Methylphenol (o-Cresol) | µg/L | N/A | ND | ND - 12 | ND - 19 | -- | -- | -- | -- | -- | ND |
| Benzoic acid | µg/L | N/A | ND | ND | 150 - 280 | -- | -- | -- | -- | -- | ND |
| Benzyl alcohol | µg/L | N/A | ND | ND | ND - 12 | -- | -- | -- | -- | -- | ND |
| Bis(2-Ethylhexyl) Phthalate | µg/L | N/A | ND | ND | 13 - 32 | -- | -- | -- | -- | -- | ND |
| Diethyl Phthalate | µg/L | N/A | ND | ND - 12 | 18 - 21 | -- | -- | -- | -- | -- | ND |
| Di-n-Butyl Phthalate | µg/L | N/A | ND | ND | ND - 16 | -- | -- | -- | -- | -- | ND |
| **Biological Parameters** | | | | | | | | | | | |
| Total Coliforms | MPN/100 mL | N/A | 2300 | > 160000 | > 160000 | ND | ND | ND | ND | -- | -- |
| Fecal Coliform | MPN/100 mL | N/A | 2300 | 90000 | 160000 | ND | ND | ND | ND | -- | -- |
| E. coli | MPN/100 mL | N/A | 5040 | 73800 | 18500 | ND | ND | ND | ND | -- | -- |

1. Units of measure: mg/L = milligrams per liter, µg/L = micrograms per liter, MPN/100 mL = most probable number per 100 milliliters.
2. "--" indicates the constituent was not analyzed for. Analytes not detected are indicated by ND.



A005585

## Table 11 Summary Results - Veterans Park

| | | | Monitoring Station[2] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Constituent | Units[1] | Fraction | V-SW-01 | V-SW-02 | V-LS-01 | V-LS-02 | V-MW-01 | V-MW-02 | V-MW-03 | V-MW-04 |
| General Monitoring Parameters | | | | | | | | | | |
| Nitrate (as N) | mg/L | N/A | 0.11 - 0.95 | ND - 1.9 | 1.6 - 4.4 | 0.91 - 8.9 | 2.3 - 4.7 | 0.56 - 3.7 | 2.1 - 6 | 20 - 44 |
| Total Kjeldahl Nitrogen | mg/L | N/A | 2.5 - 10 | 4.2 - 6.6 | 0.56 - 1.4 | 0.98 - 3.4 | 0.42 - 0.84 | ND - 0.98 | ND - 0.98 | 0.98 - 1.7 |
| Ammonia-Nitrogen | mg/L | N/A | 0.6 - 1.6 | 0.21 - 1.8 | ND | ND - 0.56 | ND | ND | ND | ND |
| Total Dissolved Solids | mg/L | N/A | 20 - 290 | 130 - 470 | 610 - 2700 | 2200 - 4000 | 4200 - 6000 | 1500 - 2900 | 1300 - 2100 | 4300 - 6600 |
| Total Suspended Solids | mg/L | N/A | 20 - 390 | 42 - 210 | -- | -- | 4.1 - 43 | ND - 28 | ND - 110 | ND - 230 |
| Chemical Oxygen Demand | mg/L | N/A | 53 - 530 | 150 - 690 | ND - 23 | 41 - 250 | 61 - 90 | 13 - 75 | ND - 94 | 46 - 160 |
| Chloride | mg/L | N/A | 1.6-26 | 5.2-31 | 12-240 | 180-440 | 1000-1400 | 130-180 | 130-180 | 820-1400 |
| Metals | | | | | | | | | | |
| Aluminum | µg/L | Dissolved | ND - 67.7 | ND - 120 | ND | ND | ND - 65.3 | ND | ND - 141 | ND - 218 |
| Aluminum | µg/L | Total | 302 - 2140 | 491 - 2740 | ND | ND | 108 - 612 | 51.4 - 805 | ND - 1440 | 55.7 - 1900 |
| Arsenic | µg/L | Dissolved | ND - 1.03 | ND - 1.94 | 16.1 - 29 | 5.34 - 8.16 | 2.41 - 19.6 | 5.32 - 10.6 | 1.9 - 5.83 | 5.17 - 17.7 |
| Arsenic | µg/L | Total | ND - 1.79 | 0.584 - 2.54 | 16 - 29.3 | 5.22 - 9.28 | 4.85 - 19.6 | 6.03 - 12.1 | 1.96 - 6.03 | 5.79 - 17.5 |
| Cadmium | µg/L | Dissolved | ND | ND - 0.316 | 0.23 - 0.41 | ND - 0.306 | ND - 0.285 | ND | ND | ND |
| Chromium, Hexavalent | µg/L | Dissolved | ND - 0.67 | 0.29 - 1.4 | 0.88 - 1.3 | ND | ND - 0.27 | 0.51 - 2.9 | ND - 2.7 | ND |
| Copper | µg/L | Dissolved | 7.37 - 24.1 | 8.77 - 33.8 | 3.26 - 6.49 | 9.03 - 20.7 | 2.93 - 5.04 | 2.27 - 6.74 | 2.14 - 3.57 | 4.82 – 200 |
| Copper | µg/L | Total | 11.4 - 45.9 | 23 - 52.3 | 3.18 - 7.76 | 9.41 - 23.6 | 2.72 - 6.2 | 2.37 - 7.94 | 2.13 - 5.39 | 6.01 – 228 |
| Lead | µg/L | Dissolved | ND - 3.41 | 0.954 - 3.3 | ND | ND | ND | ND | ND | ND - 0.536 |
| Lead | µg/L | Total | 3.96 - 27.8 | 4.59 - 22.6 | ND | ND | ND | ND - 0.712 | ND - 1.89 | ND - 2.24 |
| Mercury | µg/L | Dissolved | ND - 0.111 | ND - 0.117 | ND | ND | ND | ND - 0.105 | -0.1 - 0.164 | ND - 0.149 |
| Zinc | µg/L | Dissolved | 38.2 - 114 | 34.5 - 207 | ND - | ND - 25.8 | ND | ND - 9.9 | ND - 5.51 | ND - 25.3 |

| | | | Monitoring Station[2] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Constituent | Units[1] | Fraction | V-SW-01 | V-SW-02 | V-LS-01 | V-LS-02 | V-MW-01 | V-MW-02 | V-MW-03 | V-MW-04 |
| | | | | | 19.1 | | | | | |
| Zinc | µg/L | Total | 59.4 - 221 | 73.5 - 157 | ND - 27.3 | 13.2 - 26.2 | ND | ND - 11.7 | ND - 22.8 | ND - 28.5 |
| **Other Constituents** | | | | | | | | | | |
| MBAS (Surfactants) | mg/L | N/A | 0.24 - 1.1 | 0.11 - 0.77 | -- | -- | ND - 0.21 | ND - 0.13 | ND - 0.11 | ND - 0.35 |
| Oil and Grease | µg/L | N/A | 1.5 | 2.1 - 6.1 | -- | -- | ND - 1.2 | ND - 3.5 | ND - 7.4 | ND - 19 |
| Perchlorate | µg/L | N/A | ND | ND | ND | ND | ND - 9 | ND | ND - 4.5 | ND - 8.3 |
| Glyphosate | µg/L | N/A | ND - 16.2 | ND | ND | ND | ND | ND | ND | ND |
| **Volatile Organic Compounds** | | | | | | | | | | |
| 2-Butanone (Methylethyl ketone) | µg/L | N/A | ND - 2.9 | ND - 4.3 | ND | ND | ND | ND | ND | ND |
| Acetone | µg/L | N/A | 5.8 - 19 | 2.6 - 18 | ND - 2.5 | ND | ND | ND - 2.7 | ND | ND - 4.1 |
| Chloroform | µg/L | N/A | ND | ND | ND - 1.7 | ND - 0.95 | ND | ND | ND - 0.61 | ND |
| Dibromochloromethane | µg/L | N/A | ND | ND - 0.69 | ND | ND | ND | ND | ND | ND |
| Dichlorobromomethane | µg/L | N/A | ND | ND - 0.51 | ND | ND | ND | ND | ND | ND |
| Diethyl Ether | µg/L | N/A | ND - 0.97 | ND - 0.71 | ND | ND | ND | ND | ND | ND |
| Ethanol | µg/L | N/A | ND | ND - 250 | ND | ND | ND | ND | ND | ND |
| Methyl Chloride | µg/L | N/A | ND | ND | ND - 0.6 | ND - 0.72 | ND | ND | ND | ND |
| **Semi-Volatile Organic Compounds** | | | | | | | | | | |
| Bis(2-Ethylhexyl) Phthalate | µg/L | N/A | ND - 18 | ND - 20 | -- | -- | ND | ND | ND | ND |
| **Biological Parameters** | | | | | | | | | | |
| Total Coliforms | MPN/100 mL | N/A | 30000 | 30000 | ND | ND | ND | ND | ND | -- |
| Fecal Coliform | MPN/100 mL | N/A | ND | 700 | ND | ND | ND | ND | ND | -- |
| E. coli | MPN/100 mL | N/A | 200 | 100 | ND | ND | ND | ND | ND | -- |

1. Units of measure: mg/L = milligrams per liter, µg/L = micrograms per liter, MPN/100 mL = most probable number per 100 milliliters.
2. "--" indicates the constituent was not analyzed for. Analytes not detected are indicated by ND.

# 5. DISCUSSION

The potential influence of stormwater infiltrated during this project on soil pore fluid and groundwater quality beneath the site is discussed in this section. The following discussion focuses on analytical results for typical constituents of concern for stormwater and groundwater, including COD, copper, lead, zinc, and arsenic. Additionally, analytical results for other groundwater constituents of concern (TDS, nitrate, chloride, perchlorate, and MtBE) are discussed in detail. PAHs are not discussed as they were not detected in any sample.

TSS, a stormwater constituent of concern, and other metals are not discussed in detail because they are typically not of concern in groundwater. Cadmium, for example, was detected at low concentrations in some stormwater samples, but was not detected in groundwater with the exception of low levels in one well sample at IMAX and Veterans Park.

Analytical results are analyzed both temporally and spatially. Time-concentration charts and the results of Mann-Kendall trend analysis are contained in **Appendix F**. Depth-concentration charts, which show the variation in concentrations between each sampling point by depth, are contained in **Appendix G**. Examples of the time-concentration and depth-concentration charts are included for chloride at Veterans Park, at the end of this discussion.

## 5.1 Broadous Elementary School

Based on the relative locations and distances of the on-site groundwater monitoring wells, monitoring well B-MW-01 is considered to represent a background well in the site monitoring network. Groundwater quality at B-MW-02 is considered more likely to have been subject to potential influence by stormwater infiltrated during this study.

Nitrate

Concentrations of nitrate in stormwater samples were generally consistent and relatively lower than those in lysimeter and groundwater samples. Concentrations in lysimeter samples remained relatively consistent and low with the exception of the 2002/2003 season where nitrate concentrations were significantly higher. Nitrate concentrations in groundwater samples were slightly higher than concentrations in the lysimeters except for the noted 2002/2003 season. Nitrate concentrations in samples collected from the two groundwater wells were similar. Based on these results, stormwater infiltration has not had an adverse effect on nitrate concentration in groundwater.

TDS

TDS concentrations in stormwater samples were significantly lower than those in lysimeter and groundwater samples. TDS concentrations in lysimeter samples were variable and exhibited concentrations over a broader range. TDS concentrations in groundwater were generally consistent, decreasing slightly during the study period. Groundwater at monitoring wells B-MW-01 and B-MW-02 had similar TDS concentrations. Based on these results, stormwater infiltration has not had an adverse effect on TDS concentration in groundwater, and may have slightly improved groundwater quality as measured by TDS concentration.

Chloride

In general, chloride concentrations in stormwater samples were low and decreased slightly during the study period. Groundwater samples had slightly higher concentrations than those in stormwater samples and were generally consistent or decreased slightly. Chloride concentrations were higher in B-MW-01 than those in B-MW-02 at the beginning of the study, but then were relatively similar subsequently. Chloride concentrations in lysimeter samples were higher than those in the stormwater and groundwater samples and showed more variability but appeared to decrease slightly over the course of the study. Groundwater degradation by chloride from stormwater infiltration during the study does not appear to have occurred at this site.

Chemical Oxygen Demand

Stormwater samples generally had higher concentrations of COD than groundwater and lysimeter samples and were the most variable. COD in the lysimeter samples was higher initially and lowers toward the end of the study. Groundwater samples were slightly more consistent and had lower COD concentrations than the stormwater and lysimeter samples. COD concentrations in the groundwater samples appeared to decrease during the study. COD was slightly higher in samples from B-MW-02 than in those from B-MW-01. Although no significant trends were seen, COD concentrations appeared to decrease in all types of samples during the study period. Based on these results, stormwater infiltration for this project does not appear to have resulted in groundwater quality degradation by COD.

Total Copper

Total copper concentrations in stormwater and lysimeter samples were generally variable and within similar ranges. Total copper concentrations in groundwater samples were higher initially, but subsequently decreased and were generally lower than those in stormwater and lysimeter samples. Although total copper concentrations in stormwater samples were generally higher, it does not appear that total copper concentrations in groundwater or soil pore water increased as the result of stormwater infiltration over the study period.

Dissolved Copper

Concentrations of dissolved copper in stormwater samples were generally consistent or decreased slightly over the course of the study. Concentrations of dissolved copper in lysimeter samples were more variable and periodically were higher than those in stormwater samples; but these concentrations also decreased slightly during the study. In groundwater samples, dissolved copper concentrations were generally lower than in the other types of samples except in the first season of monitoring when the dissolved copper concentration for B-MW-02 was much higher than that for B-MW-01. Dissolved copper concentrations in groundwater samples appeared to decrease during the study. Although dissolved copper concentrations in stormwater and lysimeter sample concentrations were generally higher than those in groundwater, it does not appear that dissolved copper in groundwater or soil pore water increased as the result of stormwater infiltration over the study period.

Total Lead

Total lead was detected in all of the stormwater samples collected at Broadous, but concentrations were generally variable. Total lead was detected in only three of the lysimeter samples and, in general, total lead concentrations in lysimeter samples were lower than stormwater samples. Total lead was detected in approximately half of the groundwater samples and decreased during the study. Because concentrations of total lead decreased in groundwater samples and were not detected in most of the lysimeter samples, it does not appear that total lead in groundwater or soil pore water increased as the result of stormwater infiltration over the study period.

Dissolved Lead

Dissolved lead was detected in only one stormwater sample, at a low concentration. Dissolved lead was detected in only one groundwater sample collected at the beginning of the study from B-MW-02. Three lysimeter samples had detected concentrations of dissolved lead during the middle of the study. Based on the limited number of detected concentrations, it does not appear that dissolved lead in groundwater or soil pore water increased as the result of stormwater infiltration.

Total Zinc

Total zinc was detected in all of the stormwater samples and most of the lysimeter and groundwater samples. Concentrations of total zinc in stormwater were higher than those in lysimeter or groundwater samples. Total zinc concentrations in lysimeter samples were generally low except for during the 2002/2003 season when the concentrations were significantly higher than in stormwater or groundwater samples. In the first part of the study, lysimeter and groundwater samples were higher in total zinc concentrations than that the stormwater samples, but lower than stormwater samples in the second half of the study. By the second half of the study, total zinc decreased to low levels in all samples. Total zinc in the two groundwater monitoring wells were generally similar except in the initial part of the study when concentrations in B-MW-01 were higher than those in B-MW-02. Based on these results, it appears that stormwater infiltration does not have an adverse affect on total zinc concentrations in groundwater.

Dissolved Zinc

Dissolved zinc was detected in all of the stormwater samples and in most of the groundwater and lysimeter samples. Dissolved zinc concentrations in stormwater were generally consistent although slightly higher in the 2001/2002 and 2003/2004 season and in lysimeter samples were generally low except for the 2002/2003 season when the concentrations were significantly higher than any of the other dissolved zinc concentrations detected in any of the sample types. Dissolved zinc concentrations were generally similar in groundwater samples from the two monitoring wells except in the initial part of the study when groundwater samples from B-MW-01 were slightly higher.

In general, concentrations of dissolved zinc in all three types of samples appeared to decrease during the study. Based on these results, it does not appear that dissolved zinc in groundwater or soil pore water increased as the result of stormwater infiltration over the study period.

Arsenic
Arsenic was periodically detected in the stormwater samples from this site. Arsenic concentrations in the lysimeter samples were higher than those in the stormwater samples and were more variable during the study with a significantly higher concentration detected during the 2003/2004 season. Arsenic concentrations in groundwater samples were mainly below detection except in the samples from B-MW 01 in the beginning of the study and in samples from both B MW 01 and B-MW-02 at the end of the study. Based on these results, it does not appear that arsenic present in the stormwater or pore water has affected the water quality in the groundwater wells.

Perchlorate
Perchlorate was not detected in any lysimeter or groundwater samples. Perchlorate was detected in one stormwater sample collected during the 2003/2004 season, but not in any of the other stormwater samples. Because perchlorate was not detected in lysimeter or groundwater samples collected for this study, it does not appear that stormwater infiltration from this study has contributed to degradation of groundwater.

## 5.2 Hall House

A single lysimeter, H-LS-01, is present at the site beneath the edge of the infiltration lawn area. Because there are no groundwater monitoring wells at this site, soil pore fluid quality may be used as an indicator of potential influence on groundwater quality.

Nitrate
Concentrations of nitrate in stormwater were consistently low or not detected at H SW 01 and variable at H-SW-02. Nitrate concentrations in surface water samples collected during 2003 and 2004 were variable in comparison with those detected in lysimeter samples; surface water and lysimeter samples results for samples collected in 2005 were similar. Nitrate concentrations in lysimeter samples were relatively higher during the initial sampling event and low or non-detected and generally consistent during subsequent events. Based on these results, soil pore fluid does not appear to have been degraded by nitrate from stormwater infiltrated as part of this study.

TDS
TDS concentrations in stormwater samples were significantly lower than those in lysimeter samples. TDS data from the lysimeter were not available for the 2002/2003 season. TDS concentrations in lysimeter samples were relatively consistent during the two sampling events in the 2003/2004 season and the first event in the 2004/2005 season, then decreased during the final two events of the study. Based on these results, soil pore fluid does not appear to have been degraded by TDS from stormwater infiltrated as part of this study.

Chloride
Chloride concentrations in stormwater samples were significantly lower than those in lysimeter samples during most of the study period. TDS concentrations in lysimeter samples were variable from the initial sampling event through the first event in the 2004/2005 season, then, similar to TDS, decreased during the final two events of the study. Chloride was not detected in the lysimeter sample from the final sampling event. Based on these results, soil pore fluid does not appear to have been degraded by chloride from stormwater infiltrated as part of this study.

Chemical Oxygen Demand
COD values in stormwater were relatively consistent at H-SW-01 and variable at H-SW-02. Stormwater samples had higher concentrations of COD than did lysimeter samples. COD in lysimeter samples was not detected during the three initial sampling events for which data are available, and was detected at concentrations at or only very slightly greater than the reporting limit during the two subsequent monitoring events. Based on these results, stormwater infiltration for this project does not appear to have resulted in degradation of soil pore fluid by COD.

Total Copper
Concentrations of total copper in stormwater samples were variable and generally higher than those in lysimeter samples. Lysimeter sample concentrations of total copper were low and showed a statistically significant decreasing trend. Based on these results, soil pore fluid does not appear to have been degraded by chloride from stormwater infiltrated as part of this study.

Dissolved Copper
Concentrations of dissolved copper in stormwater samples were variable. Concentrations at H-SW-02 were in all cases higher than those in lysimeter samples; concentrations at H-SW-01 were higher than those in lysimeter samples during three sampling events and lower during three sampling events. Lysimeter sample concentrations of dissolved copper showed a statistically significant decreasing trend during the study period. Based on these results, soil pore fluid does not appear to have been degraded by chloride from stormwater infiltrated as part of this study.

Total Lead
Concentrations of total lead in stormwater samples were variable but significantly greater than those in lysimeter samples. The initial lysimeter sample for which total lead results are available (February 2004) showed a total lead concentration slightly above its reporting limit; total lead was not detected in any of the subsequent lysimeter samples from this site. Based on these results, stormwater infiltration for this project does not appear to have resulted in degradation of soil pore fluid by total lead.

Dissolved Lead
Concentrations of dissolved lead in stormwater samples were variable but significantly greater than those in lysimeter samples during most sampling events. The initial lysimeter sample (December 2002) showed a dissolved lead concentration slightly above its

reporting limit; dissolved lead was not detected in any of the subsequent lysimeter samples from this site. Based on these results, stormwater infiltration for this project does not appear to have resulted degradation of soil pore fluid by dissolved lead.

Total Zinc

Concentrations of total zinc in stormwater samples were variable but significantly greater than those in lysimeter samples. Lysimeter samples were analyzed for total zinc during February 2004 and subsequent monitoring events, and showed total zinc concentrations that were variable but did not show a clear trend. Based on these results, stormwater infiltration for this project does not appear to have resulted in degradation of soil pore fluid by total zinc.

Dissolved Zinc

Dissolved zinc was detected in all of the stormwater samples. For all sampling events, concentrations of dissolved zinc were higher at surface water sampling point H-SW-01 than at surface water sampling point H-SW-02 or in the lysimeter sample. Concentrations at H-SW-02 were generally more similar to those in the lysimeter samples. Lysimeter sample concentrations of dissolved zinc showed a statistically significant decreasing trend during the study period. Based on these results, stormwater infiltration for this project does not appear to have resulted in degradation of soil pore fluid by dissolved zinc.

Arsenic

Arsenic was detected in only one of the stormwater samples from this site (the sample collected in February 2004 from H-SW-02) and in only the initial lysimeter sample (from December 2002). Consequently, stormwater infiltration for this project does not appear to have resulted in degradation of soil pore fluid by arsenic.

Perchlorate

Perchlorate was not detected in stormwater samples from this site. Lysimeter samples from this site were not analyzed for perchlorate.

## 5.3 IMAX

Based on the relative locations and distances of the on-site groundwater monitoring wells, monitoring well I-MW-01 represents an "upgradient background" well in the site monitoring network. Groundwater quality at I-MW-02 is considered much more likely than that at I-MW-01 to have been subject to influence by stormwater infiltrated during this study.

Nitrate

Concentrations of nitrate in stormwater samples were typically lower than those in lysimeter and groundwater samples. Nitrate concentrations in lysimeter samples from I-LS-01 and I-LS-02 were significantly different, with higher concentrations in I-LS-01 (area of roof runoff). Concentrations of nitrate in I-LS-02 were typically low and decreased slightly over the study period. The decreasing concentration trend in I-LS-02 is statistically significant. Groundwater samples from both wells were similar, with slightly higher concentrations in I-MW-02 during the first two years of the study. Based on these results, stormwater infiltration for this project does not appear to have resulted in groundwater quality degradation by nitrate.

TDS

Concentrations of TDS in stormwater samples were typically lower than those in lysimeter and groundwater samples. TDS concentrations in lysimeter samples from I-LS-01 and I-LS-02 were significantly different, with higher concentrations in I-LS-01 (area of roof runoff). Lysimeter sample concentrations did not exhibit statistically significant trends over time. Concentrations from the two groundwater monitoring wells appeared to have similar concentrations with no statistically significant trends. The most recent TDS concentration from I-MW-02 (potentially influenced by infiltrated stormwater) was the lowest observed during the study period. Based on these results, stormwater infiltration for this project does not appear to have resulted in groundwater quality degradation by TDS.

Chloride

Concentrations of chloride in stormwater were typically lower than both those in lysimeter and groundwater samples. Chloride concentrations in lysimeter samples from I-LS-01 and I-LS-02 were significantly different, with higher concentrations in I-LS-01 (area of roof runoff). Lysimeter sample concentrations did not exhibit statistically significant trends over time. Samples from the groundwater monitoring well nearest the infiltrator (I-MW-02) exhibited typically higher concentrations than samples from I-MW-01 but showed a statistically significant slightly decreasing trend over the study period. Concentrations of chloride in I-MW-01 appeared relatively consistent throughout the study period. Stormwater infiltration for this project does not appear to have resulted in groundwater quality degradation by chloride.

Chemical Oxygen Demand

Concentrations of COD in stormwater appeared variable. COD in lysimeter samples were variable with slightly higher concentrations in samples from I-LS-01 over the last two years of the study. COD concentrations in groundwater were generally higher in I-MW-02 than in I-MW-01, including a notably higher concentration in the initial sample collected in 2001. No trends for COD in groundwater or lysimeter samples were apparent. Based on these results, stormwater infiltration for this project does not appear to have resulted in groundwater quality degradation by COD.

Total Copper

Concentrations of total copper in stormwater samples from I-SW-02 (parking lot runoff) were variable and typically higher than those in groundwater samples. Lysimeter sample concentrations appeared variable with slightly decreasing concentrations during the 2004/2005 wet season. Except for the initial samples collected in 2001, total copper concentrations in groundwater samples were typically low and lower than lysimeter and stormwater samples during the last two years of the study. While stormwater and lysimeter sample concentrations are generally higher than groundwater, it does not appear that total copper concentrations in groundwater or soil pore water increased as the result of stormwater infiltration over the study period.

Dissolved Copper

Concentrations of dissolved copper in stormwater samples from I-SW-02 (parking lot runoff) were variable and typically higher than those in groundwater samples. Lysimeter sample concentrations appeared variable with slightly decreasing concentrations over the study period. Except for the initial samples collected in 2001, groundwater samples were typically low and lower than both lysimeter and stormwater samples during the last two years of the study. While stormwater and lysimeter sample concentrations were generally higher than groundwater, it does not appear that total copper concentrations in groundwater or soil pore water increased as the result of stormwater infiltration over the study period.

Total Lead

Concentrations of total lead in stormwater samples were typically higher than those in lysimeter or groundwater samples. One notably higher concentration was detected at I-SW-01 during the storm event sample collected on February 18, 2005. Concentration of total lead from both lysimeter locations showed low and generally decreasing concentrations, with total lead not detected in the last two sampling events. The decreasing concentration trend in I-LS-01 is statistically significant. Total lead concentrations in groundwater were generally lower, except for the initial sampling event, in groundwater well I-MW-02 (potentially influenced by infiltrated stormwater). I-MW-02 also had a higher percentage of non-detect samples during the study period. Although concentrations of total lead were generally higher in stormwater samples than in groundwater, it does not appear that total lead in groundwater or soil pore water increased as the result of stormwater infiltration over the study period.

Dissolved Lead

Dissolved lead was detected in only one stormwater sample, one lysimeter sample, and one groundwater sample during the study. Based on the limited number of detected concentrations, it does not appear that dissolved lead in groundwater or soil pore water increased as the result of stormwater infiltration.

Total Zinc

Total zinc was detected in all of the stormwater samples. Concentrations of total zinc in stormwater were typically similar to or higher than those in groundwater samples. Lysimeter sample concentrations from I-LS-02 were highly variable with the lowest concentrations detected in the last three sample events. I-LS-01 remained generally consistent over the study duration. Total zinc concentrations in groundwater samples were typically lower than those in stormwater and in the majority of lysimeter samples. Total zinc concentrations were generally lower in groundwater well I-MW-02 than in I-MW-01 in all but the initial and most recent samples. Although concentrations of total zinc were generally higher in stormwater samples than in groundwater, it does not appear that total zinc in groundwater or soil pore water increased as the result of stormwater infiltration over the study period.

Dissolved Zinc

Dissolved zinc was detected in all of the stormwater samples. Concentrations of dissolved zinc in stormwater were typically higher than those in groundwater samples. Lysimeter sample concentrations in I-LS-02 appeared variable with slightly decreasing concentrations during the 2004/2005 wet season. Lysimeter sample concentrations in I-LS-02 appeared variable with slightly increasing concentrations during the 2004/2005 wet season. Dissolved zinc concentrations in groundwater samples were typically lower than those in stormwater and in the majority of lysimeter samples. Dissolved zinc concentrations were generally lower in groundwater well I-MW-02 than in I-MW-01 in all but the initial and most recent samples. Although concentrations of dissolved zinc were generally higher in stormwater samples than in groundwater, it does not appear that dissolved zinc in groundwater or soil pore water increased as the result of stormwater infiltration over the study period.

Arsenic

Arsenic was not detected in stormwater samples collected from I-SW-01 (roof runoff). Arsenic concentrations in stormwater from I-SW-02 (parking lot runoff) were variable but generally higher than groundwater and lysimeter sample concentrations. Lysimeter sample concentrations from I-LS-02 remained relatively consistent or decreased slightly over the study period. Lysimeter sample concentrations from I-LS-01 were relatively low but may have increased slightly. Samples from both groundwater monitoring wells showed similar concentrations with no statistically significant trends. While stormwater sample concentrations are generally higher than soil pore water and groundwater, it does not appear that arsenic concentrations in groundwater or soil pore water increased as the result of stormwater infiltration over the study period.

Perchlorate

Perchlorate was detected in only one stormwater sample and was not detected in lysimeter samples from this site. Perchlorate concentrations in I-MW-02 were typically higher than at I-MW-01 but appeared to decrease slightly over the study duration. Perchlorate concentrations in I-MW-01 were variable with a slightly increasing trend over the duration of the study. Perchlorate was also detected in groundwater samples taken at the beginning of the study, thus it is likely a pre-existing condition and not a result of stormwater infiltration.

MtBE

MtBE was not detected in the majority of the stormwater and lysimeter samples. MtBE concentrations were variable in groundwater well I-MW-02 with no detections since 2003. MtBE was not detected in I-MW-01. Because MtBE was only detected in one stormwater and lysimeter sample, it does not appear that stormwater infiltration from this study has contributed MtBE to groundwater.

## 5.4 Metal Recycler

At the metal recycler site, groundwater occurs at more than 200 feet bgs. A single groundwater monitoring well, M-MW-01, was constructed approximately 25 feet south of the infiltrator.

Nitrate
Concentrations of nitrate in stormwater were generally near the lower portion of the range of concentrations in lysimeter samples. Nitrate was detected in the baseline sample from well M-MW-01 at a concentration just above its detection limit. Nitrate was not detected in any of the subsequent groundwater samples. There was not a consistent concentration trend with depth in samples collected from the two sets of shallow/deep paired lysimeters at the site. Nitrate concentrations in samples from deep lysimeter M-LS-01 were generally similar to or greater than those in samples from its paired shallower lysimeter, M-LS-02. However, both samples collected from deep lysimeter M-LS-03 had lower concentrations than those in samples from its shallower companion, M-LS-04. Concentrations in stormwater and lysimeter samples remained relatively consistent during the study, and nitrate was not detected in groundwater samples after the initial sampling event.

TDS
TDS concentrations in stormwater samples had an average concentration of about 1000 mg/L. TDS concentrations in lysimeter and groundwater samples were similar. There is no apparent trend in concentration with depth in samples collected from the two sets of paired lysimeters. Concentrations in stormwater, lysimeter, and groundwater samples remained relatively consistent during the study.

Chloride
Chloride concentrations were generally similar in stormwater, lysimeter, and groundwater samples. Chloride concentrations in samples collected from deep lysimeter M-LS-03 were consistently higher than those in samples from its shallow pair, M-LS-04. Concentrations in stormwater and lysimeter samples remained relatively consistent during the study. An increasing trend in chloride concentration in groundwater samples collected from M-MW-01 is statistically significant. Because groundwater is deep and because chloride concentrations in stormwater and lysimeter samples is similar to those in groundwater, it is likely that the increasing trend in chloride in groundwater samples is due to factors other than stormwater infiltration.

Chemical Oxygen Demand
Stormwater samples generally had higher concentrations of COD than groundwater and lysimeter samples. No time or depth trends for COD in groundwater or lysimeter samples are evident. Based on these results, stormwater infiltration for this project does not appear to have resulted in groundwater quality degradation by COD.

Total Copper
Concentrations of total copper in stormwater samples were variable and consistently higher than those in lysimeter samples and groundwater. Concentrations in lysimeter samples

were variable and consistently higher than those in groundwater samples. Samples collected from deep lysimeter M-LS-03 had a consistently lower concentration than did those in samples collected from its shallower companion, M-LS-04. No concentration trends are evident for the study period. While stormwater and lysimeter sample concentrations are consistently higher than groundwater concentration, it does not appear that total copper concentrations in groundwater or soil pore water increased as the result of stormwater infiltration over the study period.

Dissolved Copper

Concentrations of dissolved copper in stormwater samples were variable and consistently higher than those in lysimeter samples. Concentrations in lysimeter samples were variable and consistently higher than those in groundwater samples. Samples collected from deep lysimeter M-LS-03 had a consistently lower concentration than detected in samples collected from its shallower companion, M-LS-04. No concentration trends are evident for the study period. While stormwater and lysimeter sample concentrations were consistently higher than groundwater concentrations, it does not appear that dissolved copper concentrations in groundwater or soil pore water increased as the result of stormwater infiltration over the study period.

Total Lead

Concentrations of total lead in stormwater samples were variable and consistently higher than those in lysimeter samples. Concentrations in lysimeter samples were variable and consistently higher than those in groundwater samples. No concentration trends with depth are evident in the paired lysimeters, but concentrations in samples from the M-LS-01/M-LS-02 pair were consistently higher than those in samples from the M-LS-03/M-LS-04 pair. No concentration trends with time were evident for the study period. Although stormwater and lysimeter sample concentrations were consistently higher than groundwater concentrations, it does not appear that total lead concentrations in groundwater or soil pore water increased as the result of stormwater infiltration over the study period.

Dissolved Lead

Dissolved lead was detected in all stormwater samples at concentrations ranging from about 3 to 180 μg/L. Dissolved lead was detected in lysimeter samples at concentrations less than 7 μg/L, and was not detected in about half the samples. Dissolved lead was not detected in groundwater samples. Based on the limited number of detected concentrations, it does not appear that dissolved lead in groundwater or soil pore water increased as the result of stormwater infiltration.

Total Zinc

Concentrations of total zinc in stormwater samples were variable and consistently much higher than those in lysimeter or groundwater samples. Concentrations in lysimeter samples were variable and consistently higher than those in groundwater samples. There are no evident concentration trends with depth in the paired lysimeters, but concentrations in samples from the M-LS-01/M-LS-02 pair were consistently higher than those in samples from the M-LS-03/M-LS-04 pair. There are no evident concentration trends over time during the study period. While stormwater and lysimeter sample concentrations are consistently higher than groundwater concentrations, it does not appear that total lead concentrations in groundwater or soil pore water increased as the result of stormwater infiltration over the study period.

Dissolved Zinc

Dissolved zinc was detected in all of the stormwater samples. Concentrations of dissolved zinc in stormwater were variable and were similar to or higher than those in lysimeter samples. Concentrations in the lysimeter samples were consistently higher than those in groundwater samples. Although concentrations of dissolved zinc were generally higher in stormwater samples than in groundwater, it does not appear that dissolved zinc in groundwater or soil pore water increased as the result of stormwater infiltration over the study period.

Dissolved Arsenic

With the exception of two samples from M-LS-03, dissolved arsenic concentrations in stormwater, lysimeter, and groundwater samples were similar at approximately 6 µg/L or less. There are no evident trends in concentration during the study period. Concentrations in samples from the deep lysimeters (M-LS-01 and M-LS-03) were generally greater than concentrations in samples from the shallow lysimeters (M-LS-02 and M-LS-04).

Perchlorate

Perchlorate was detected in most stormwater and lysimeter samples from this site. Perchlorate was not detected in groundwater samples. Although a statistically significant trend was not evident, the perchlorate data from M-LS-01 suggests greater variability and detection of sporadically higher concentrations during the later times of the study.

MtBE

MtBE was detected in a few stormwater samples in concentrations consistently less than those in lysimeter samples. The highest concentrations were detected in samples collected from the M-LS-01/M-LS02 lysimeter pair. An increasing trend in MtBE concentration in M-LS-01 is statistically significant. Because of low stormwater MtBE concentration, infiltrating stormwater is not the likely source of increasing MtBE concentration in soil pore water.

## 5.5 Sun Valley

At the Sun Valley site, groundwater occurs at more than 300 feet bgs. The potential influence of stormwater infiltrated during this project on groundwater quality in off-site well EV-10 is not considered likely. However, groundwater quality conditions in EV-10 may represent background groundwater quality conditions for the site.

Nitrate

Concentrations of nitrate detected in stormwater samples were generally low and consistent during the study. Nitrate concentrations were slightly higher in most of the lysimeters than in the stormwater samples. Nitrate concentrations in samples from shallow lysimeters S-LS-01 and S-LS-03 showed a statistically significant decrease during the study; concentrations in mid-depth lysimeter S-LS-04 were more erratic but also appeared to decrease. Nitrate concentrations in S-LS-02 were variable. Nitrate concentrations in S-LS-05 were non-detect to low. Nitrate concentrations generally were lower in the shallower lysimeters than in the mid-depth lysimeters, but the deep lysimeter S-LS-05 had very low concentrations. Nitrate was detected in well EV-10 at similar and low concentrations the two times it was sampled.

<u>TDS</u>

TDS concentrations in stormwater samples were generally low with the exception of one sample each from S-SW-02 and S-SW-03 during the second year of monitoring, when concentrations were much higher (near 1000 mg/L). Concentrations in S-SW-01, from the roof sampling point, were generally low and decreased during the study. TDS concentrations in the shallow lysimeters S-LS-01 and S-LS-03 and in the mid-depth lysimeter S-LS-04 decreased during the study but were variable in S-LS-02. The decreasing trends in TDS concentration in samples from S-LS-01 and S-LS-03 were statistically significant. Deep lysimeter S-LS-05 had an initially high TDS concentration, but the concentration decreased in the next two sampling events. The initially high TDS concentration may have been caused by dewatering of grout from this recently installed lysimeter. TDS concentrations in well EV-10, which was only sampled twice, were generally low. Based on these results, there may be a trend in depth for TDS in soil pore concentrations where TDS increases in depth, particularly at lysimeter pair S-LS-01/S-LS-02. It appears that stormwater infiltration does not have an adverse effect on pore water at the site.

<u>Chloride</u>

Chloride concentrations in stormwater samples were generally similar to or lower than those in lysimeter samples. In stormwater samples collected at S-SW-01, chloride concentrations were mainly below detection but concentrations in stormwater samples S-SW-02 and S-SW-03 were more variable. Chloride concentrations in shallow and mid-depth lysimeter samples generally decreased during the study; decreasing trends in S-LS-02 and S-LS-03 were statistically significant. Chloride concentrations in deep lysimeter S-LS-05 were significantly higher than those in the other lysimeters. In general, chloride concentrations were slightly higher in the mid-depth lysimeters versus the shallow lysimeter pairs. Chloride concentrations in samples collected from deep lysimeter S-LS-04 were consistently higher than those in samples from its shallow pair, S-LS-03. In the groundwater samples collected from EV-10, chloride concentrations were generally low and consistent.

<u>Chemical Oxygen Demand</u>

Stormwater samples generally had higher concentrations of COD than groundwater and lysimeter samples. Of the three stormwater locations, S-SW-01 had the lowest and most consistent COD concentrations with a slight decreasing trend over the course of the study. COD was detected in approximately half of the lysimeter samples. No time or depth trends for COD in lysimeter samples are evident. COD concentrations detected in groundwater samples from EV-10 were just above the reporting limit.

Total Copper

Concentrations of total copper in stormwater samples were variable and consistently higher than those in lysimeter samples. Concentrations in lysimeter samples were similar to those in groundwater samples from EV-10 except that S-LS-04, a mid-depth lysimeter, had relatively high total copper concentrations in the first year of monitoring. Total copper concentrations appeared to increase slightly in the lysimeters. A slight but statistically significant increasing trend was noted in samples from S-LS-03. No significant differences in concentrations were noted between the different lysimeters, except that the deeper lysimeter S-LS-05 had slightly lower concentrations than the other lysimeters. Because total copper concentration in lysimeter samples was low and generally remained stable or increased slightly, it does not appear that soil pore water quality was adversely impacted by total copper.

Dissolved Copper

Concentrations of dissolved copper in stormwater samples were generally higher in the samples from S-SW-02 and S-SW-03. Concentrations were variable from S-SW-02, and concentrations from S-SW-03 showed a decreasing trend. Concentrations from S-SW-01 (roof run-off), were generally consistent and low. Dissolved copper concentrations in stormwater samples were generally higher than those in lysimeter samples with the exception of S-LS-04, a mid-depth lysimeter, which had relatively high dissolved copper concentrations in the first year of monitoring. The deep lysimeter S-LS-05 had slightly lower concentrations than the other lysimeters. Dissolved copper concentrations appeared to increase slightly in the lysimeters. A slight but statistically significant increasing trend was noted in concentrations from S-LS-01 and S-LS-03. Concentrations in lysimeter samples were higher than those in the groundwater samples collected from EV-10. While stormwater concentrations are higher than lysimeter sample concentrations, it does not appear that dissolved copper concentrations in soil pore water increased significantly as the result of stormwater infiltration over the study period.

Total Lead

In general, concentrations of total lead in stormwater samples were higher than those in lysimeter samples. Concentrations of total lead in stormwater samples at S-SW-02 and S-SW-03 were variable and consistently higher than those in the stormwater samples at S-SW-01, in which they appeared to decrease slightly and were generally more consistent. Total lead was detected in approximately half of the lysimeter samples, and when detected, were generally low. No concentration trends were evident with depth in the lysimeters. Total lead in the groundwater samples collected from EV-10 also was low. While stormwater concentrations are consistently higher than lysimeter concentrations, it does not appear that total lead concentrations in soil pore water increased significantly as the result of stormwater infiltration over the study period.

Dissolved Lead

Dissolved lead was detected in most of the stormwater samples, but at generally low concentrations except in one sample at S-SW-03, which was significantly higher than the other concentrations. Dissolved lead was detected in lysimeter samples at concentrations less than 2 μg/L and was not detected in most of the samples. Dissolved lead was not detected in the groundwater samples collected from EV-10. Based on the relatively few detections of dissolved lead, it does not appear that dissolved lead in soil pore water increased as the result of stormwater infiltration.

Total Zinc

Concentrations of total zinc in stormwater samples were variable and consistently much higher than those in lysimeter samples. Concentrations in groundwater samples from EV-10 were similar to those in the lysimeter samples. Concentrations of total zinc were generally lower in the shallower lysimeters than in the deeper lysimeters. While stormwater concentrations are consistently higher than lysimeter concentrations, it does not appear that total zinc concentrations in soil pore water increased as the result of stormwater infiltration over the study period. Samples from EV-10 appear to indicate that zinc is present in regional groundwater at higher concentrations than what is detected in the lysimeters.

Dissolved Zinc

Dissolved zinc was detected in all of the stormwater samples. Concentrations of dissolved zinc in stormwater samples were variable except for samples at S-SW-01, which were fairly consistent, and were similar to or higher than those in lysimeter samples. Concentrations of dissolved zinc in lysimeter samples were generally low and consistent. Concentrations of dissolved zinc were generally lower in the shallower lysimeters than in the deeper lysimeters. Groundwater samples from EV-10 were lower in the first sampling event than the samples collected at the site and higher than most of the lysimeter samples and lower than the stormwater samples in the second sampling event. Although concentrations of dissolved zinc were generally higher in stormwater samples than in lysimeter samples, it does not appear that dissolved zinc in soil pore water increased as the result of stormwater infiltration over the study period.

Dissolved Arsenic

Dissolved arsenic concentrations in stormwater samples were generally similar to or lower than those in lysimeter samples. Dissolved arsenic was not detected in any samples from S-SW-01 and, for the other stormwater locations, the concentrations were lower in the samples collected in the second season of monitoring than in the first season of monitoring. Dissolved arsenic concentrations in lysimeter samples were consistent or decreased slightly, except for the deepest lysimeter S-LS-05, which had increasing concentrations of which the last two concentrations were significantly higher than any of the other samples for the other lysimeters. The slightly decreasing trends in dissolved arsenic concentrations in S-LS-01 and S-LS-04 were statistically significant. No evident trends were noted with depth for the lysimeters. Dissolved arsenic was not detected in groundwater from EV-10 during the initial monitoring event and was detected at a concentration only slightly above the reporting limit in the second monitoring event.

Perchlorate

Perchlorate was detected in the initial stormwater samples from S-SW-02 and S-SW-03 but was not detected in any of the subsequent samples or in any of the samples from

S-SW-01. Perchlorate was detected sporadically in lysimeters S-LS-03 and S-LS-04, with concentrations decreasing with depth. Perchlorate concentrations detected in the stormwater samples were similar to those detected in the lysimeter samples. Perchlorate was not detected in the deepest lysimeter or in groundwater samples collected at EV-10.

MtBE

MtBE was not detected in any of the stormwater samples or in the groundwater samples from EV-10. MtBE was detected in only two lysimeters (lysimeter pair S-LS-02 and S-LS-04) during the first year of monitoring. Because MtBE was not detected in any stormwater samples, infiltrating stormwater is not a likely source of MtBE concentrations in soil pore water.

TKN

TKN was detected in all of the stormwater samples and in most of the lysimeter samples. TKN concentrations generally were higher in the stormwater samples than in the lysimeter samples with the exception of one lysimeter sample (S-LS-05). TKN concentrations in the lysimeter samples were consistent and low. TKN was detected in only one of the two groundwater samples collected from EV-10 at a concentration just above the reporting limit.

## 5.6 Veterans Park

Based on the relative locations and distances of the on-site groundwater monitoring wells, there is not a clear "background" well in the site monitoring network. The monitoring wells at the site were used for interpretation of groundwater quality data in the following context:

- Based on its distance from the infiltrator, groundwater at monitoring well V-MW-01 is considered less likely to have been subject to influence by stormwater infiltrated during the study.
- Because of its proximity to the infiltrator, groundwater quality at V-MW-02 is considered more likely to have been subject to influence by stormwater infiltrated during this study.
- Groundwater quality at V-MW-03 is considered to have a moderate likelihood to have been subject to influence by stormwater infiltrated during this study.
- Groundwater quality at V-MW-04 is considered to have a moderate likelihood to have been subject to influence by stormwater infiltrated during this study.

Nitrate

Concentrations of nitrate in stormwater were relatively lower than those in lysimeter and groundwater samples. Concentrations in lysimeter samples remained relatively consistent or may have decreased slightly during the study. Groundwater samples from the well nearest the infiltrator (V-MW-02) showed concentrations of nitrate that were lower than those in samples from other wells but increased slightly during the study. Groundwater samples from V-MW-04 showed nitrate concentrations that were much higher than those from other wells but decreased during the study. Using the Mann-Kendall test for trend, decreasing concentration trends in samples collected from V-LS-02, V-MW-03, and V-MW-04 are statistically significant. The observed increasing trend in samples collected V-MW-02 is also statistically significant. The relationships, if any, between the changes in nitrate concentrations at these monitoring wells and the infiltration of stormwater for this project, were not apparent from the data reviewed.

TDS

TDS concentrations in stormwater samples were significantly lower than those in lysimeter and groundwater samples. TDS concentrations in lysimeter samples generally decreased over the study period. Groundwater at monitoring wells V-MW-01 and V-MW-04 had significantly higher concentrations of TDS than did groundwater at monitoring wells V-MW-02 and V-MW-03; this relationship was apparent in initial samples as well as samples collected later during the study. Similar to the lysimeter samples, TDS concentrations at all four groundwater monitoring wells decreased over the study period. These concentration decreases may have been the result of infiltration of relatively low-TDS stormwater to shallow groundwater, both through the project infiltrator and through the landscaped area comprising much of the site. Decreasing concentration trends in samples collected from V-LS-02, V-MW-02, and V-MW-04 are statistically significant.

Chloride

Time-concentration and depth-concentration charts for chloride are presented in Figures 10 and 11. Chloride was not detected in stormwater samples from this site during the study period. Samples from both lysimeters showed decreasing chloride concentrations. Groundwater samples from wells V-MW-01 and V-MW-04 had significantly higher concentrations of chloride than did those from V-MW-02 and V-MW-03; these differences were apparent in data from the initial sampling and subsequent events. Chloride concentrations in groundwater at V-MW-04 and V-MW-02 decreased over the duration of the study, while those at V-MW-03 were relatively consistent, and those at V-MW-01 appeared variable. Decreasing concentration trends in samples collected from V-LS-01, V-LS-02, V-MW-02, and V-MW-04 were statistically significant. Groundwater degradation by chloride from stormwater infiltration during the study does not appear to have occurred at this site, and some improvement to groundwater quality may have occurred.

Chemical Oxygen Demand

Stormwater samples generally had higher concentrations of COD than groundwater and lysimeter samples. COD in lysimeter samples were variable, with slightly higher concentrations in V-LS-02. COD concentrations in groundwater also were variable, with slightly higher concentrations in V-MW-04. No trends for COD in groundwater or lysimeter samples are evident. Based on these results, stormwater infiltration for this project does not appear to have resulted in groundwater quality degradation by COD.

Total Copper

Concentrations of total copper in stormwater samples were variable and generally higher than those in groundwater samples and the majority of those in the lysimeter samples.

Lysimeter sample concentrations of total copper were generally slightly higher in V-LS-02 than V-LS-01, with V-LS-02 concentrations typically higher than concentrations found in groundwater. V-MW-04 had slightly higher concentrations of total copper than the other three groundwater wells. V-MW-03 sample concentrations were generally lower than the other groundwater wells and concentrations at V-MW-02 showed a slight but statistically significant decreasing trend over the project period. Although stormwater and lysimeter sample concentrations are generally higher than groundwater, it does not appear that total copper concentrations in groundwater or soil pore water increased as the result of stormwater infiltration over the study period.

<u>Dissolved Copper</u>
Concentrations of dissolved copper in stormwater samples were variable and generally higher than those in groundwater samples and those in the majority of the lysimeter samples. Lysimeter sample concentrations of dissolved copper were generally slightly higher in V-LS-02 than in V-LS-01, with V-LS-02 concentrations typically higher than concentrations found in groundwater. V-MW-04 had slightly higher concentrations of dissolved copper than the other three groundwater wells. Dissolved copper concentrations in samples from V-MW-03 were generally lower than those in samples from the other groundwater wells, and concentrations at V-MW-02 showed a slight but statistically significant decreasing trend over the project period. Although dissolved copper concentrations in stormwater and lysimeter sample concentrations were generally higher than those in groundwater, it does not appear that dissolved copper in groundwater or soil pore water increased as the result of stormwater infiltration over the study period.

<u>Total Lead</u>
Concentrations of total lead in stormwater samples from V-SW-02 were typically higher than those in groundwater samples, as were the most recent samples from V-SW-01. Total lead was not detected in any lysimeter samples collected. Total lead was also not detected in groundwater samples from V-MW-01. Concentrations of total lead detected in groundwater samples from the other three wells were generally low and varied through the study period. Although concentrations of total lead were generally higher in stormwater samples than in groundwater, it does not appear that total lead in groundwater or soil pore water increased as the result of stormwater infiltration over the study period.

<u>Dissolved Lead</u>
Dissolved lead was detected at low concentrations in the majority of stormwater samples. Dissolved lead was detected in only one of the groundwater samples, and was not detected in any of the lysimeter samples. Based on the limited number of detected concentrations, it does not appear that dissolved lead in groundwater or soil pore water increased as the result of stormwater infiltration.

<u>Total Zinc</u>
Total zinc was detected in all of the stormwater samples. Concentrations of total zinc in stormwater were higher than those in lysimeter or groundwater samples. Total zinc concentrations in lysimeter samples remained generally consistent over the study duration. Total zinc was not detected in groundwater samples from V-MW-01, and concentrations in

V-MW-04 were generally higher than those in V-MW-02 and V-MW-03, but concentrations at each monitoring well remained relatively consistent during the study. Although concentrations of total zinc were generally higher in stormwater samples than in groundwater, it does not appear that total zinc in groundwater or soil pore water increased as the result of stormwater infiltration over the study period.

Dissolved Zinc

Dissolved zinc was detected in all of the stormwater samples. Concentrations of dissolved zinc in stormwater were higher than lysimeter and groundwater sample concentrations in all cases. Some lysimeter sample concentrations were slightly higher than those in the groundwater samples. Concentrations of dissolved zinc were generally similar in groundwater samples from the four monitoring wells. Lysimeter and groundwater sample concentrations were fairly stable over the study duration. Although concentrations of dissolved zinc were generally higher in stormwater samples than in groundwater, it does not appear that dissolved zinc in groundwater or soil pore water increased as the result of stormwater infiltration over the study period.

Arsenic

Arsenic was not detected in most of the stormwater samples; low concentrations were detected during the two most recent sampling events. Arsenic concentrations in lysimeter samples remained relatively consistent over the study period. Arsenic concentrations in groundwater samples from V-MW-01 and V-MW-04 were slightly higher than those from V-MW-02 and V-MW-03 during the 2004/2005 wet season, and concentrations at V-MW-02 and V-MW-03 showed a slight decrease during the study period. Based on these results and the groundwater flow and monitoring well location conditions summarized previously, it does not appear that the increase in arsenic concentrations in groundwater at V-MW-01 and V-MW-04 is the result of arsenic concentrations in stormwater infiltrated during this study. Decreasing concentration trends in samples collected from V-MW-02 and V-MW-03 are statistically significant.

Perchlorate

Perchlorate was not detected in stormwater or lysimeter samples from this site. Concentrations of perchlorate in groundwater were sporadic and variable, and included some relatively higher values in samples from V-MW-01 and V-MW-04. Because perchlorate was not detected in lysimeter or stormwater samples, it is unlikely that stormwater infiltration has contributed perchlorate to groundwater.

MtBE

MtBE was not detected in any of the samples.

# Figure 10
## Depth Concentrations for Chloride - Veterans Park

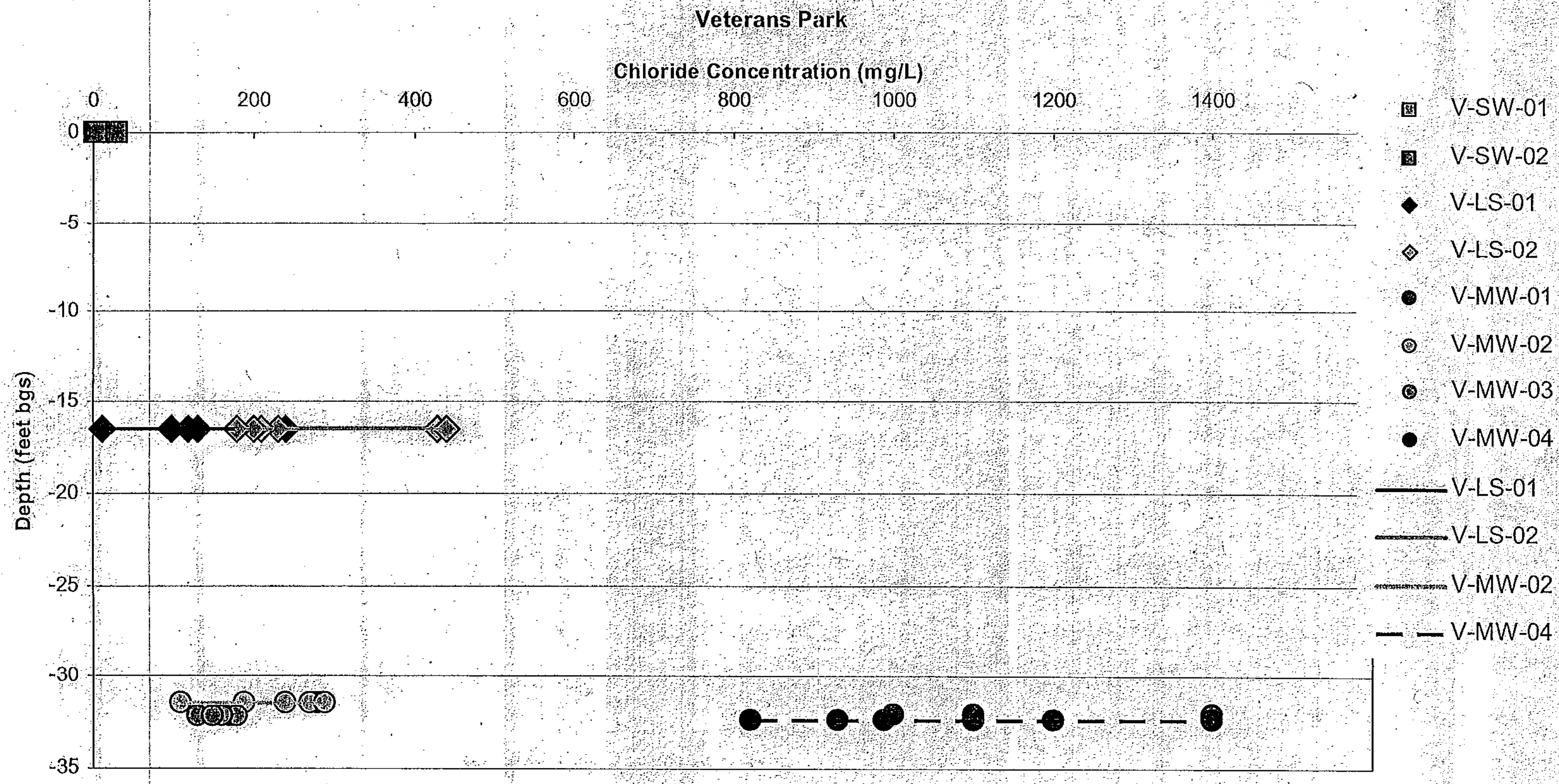
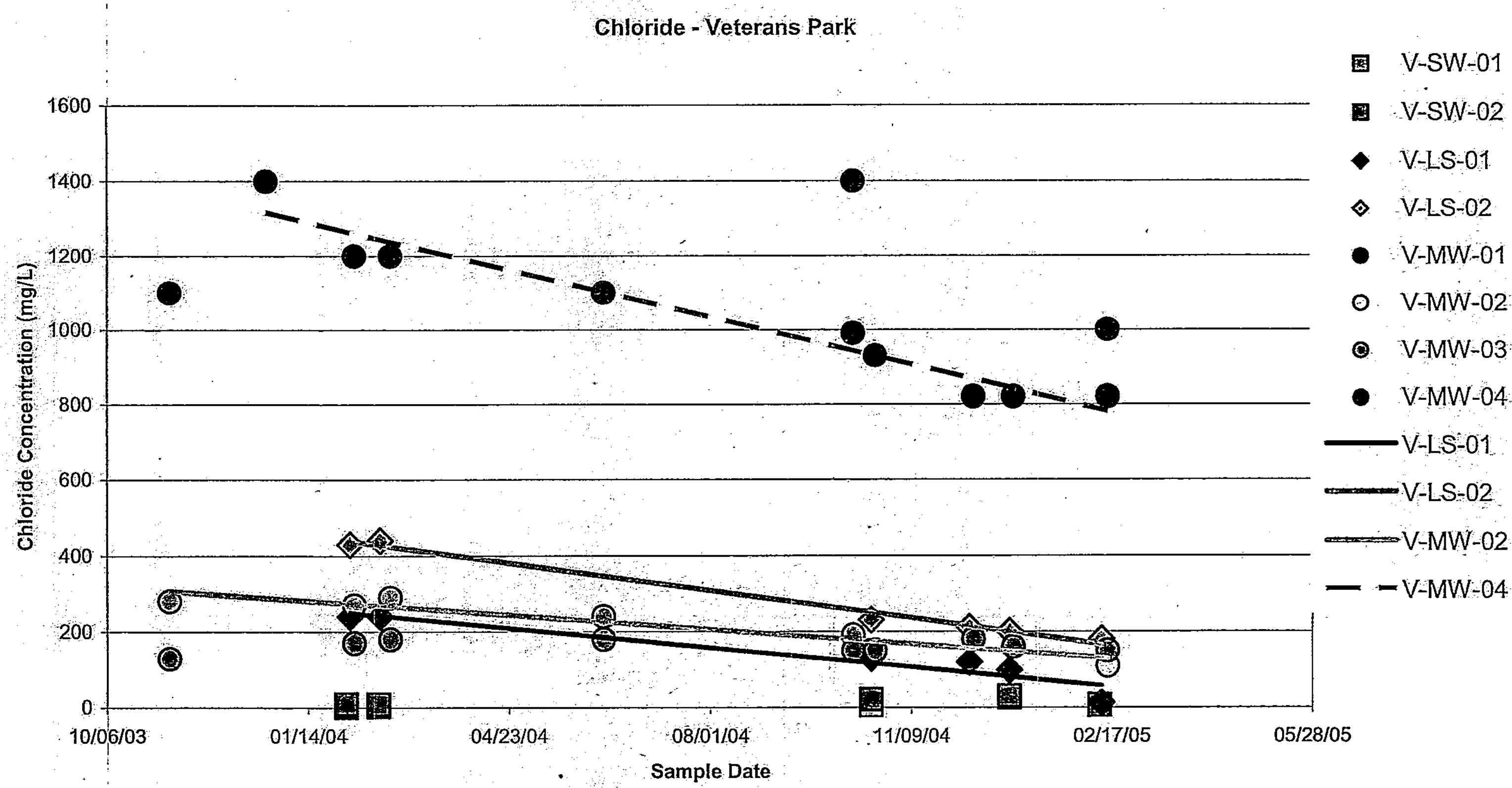


**Figure 11**
**Chloride Concentrations Over Time - Veterans Park**



## 5.7 Land Use Variation

The biggest difference in constituents detected between the sites that can be attributed to land use is in the organic compounds. Some VOCs were detected in stormwater collected at all sites, but were much more abundant in the samples collected at the industrial sites. Organics detected at the non-industrial sites were primarily acetone, MEK and oil and grease. The industrial sites had higher concentrations of those constituents, plus other compounds such as benzene, toluene, ethanol, and phthalates. Petroleum hydrocarbons were also detected in small quantities at the industrial sites, but not at the other sites.

Nitrate in stormwater was low at all sites. Concentrations of metals, dissolved solids and suspended solids were higher at the industrial sites than at the other sites, undoubtedly related to the business activities conducted at those sites. Total copper and zinc were lowest at the Broadous School. Concentrations of TDS at Veterans Park were higher in lysimeters and groundwater than samples collected at the industrial sites, which may be the result of pre-study infiltration from irrigation and the application of fertilizer that does not occur at industrial sites. No other significant differences in constituent concentrations were discernable between the commercial, educational, and residential land uses.

Total coliform bacteria concentrations were high in most stormwater samples. Detections of total coliform were highest at Sun Valley and lowest at the residential site and the metal recycler. Differences in the two industrial sites may be attributed to the types of material handled. Beverage containers brought in for sorting at the Sun Valley site may contain residual liquid that would promote bacterial growth, as opposed to the relatively dry scrap metal handled at the metal recycler.

At the three sites where roof runoff was sampled (IMAX, Hall House and Sun Valley), concentrations of most constituents were lower in roof samples than in samples taken from the ground surface. Concentrations of metals (especially total aluminum, lead and zinc), TDS, TSS and acetone in roof runoff were not insignificant however, indicating that atmospheric deposition may be a major contributor to stormwater pollution.

## 5.8 CONCLUSIONS

Soil appears to be very efficient at removing bacteria from stormwater. Fecal coliform and E. coli were detected in at least one stormwater sample from each site except Hall House, and total coliforms were detected at high levels in nearly all stormwater samples at all sites. With the exception of one sample at the Broadous School, bacteria were not detected, or detected at very low concentrations, in lysimeter and groundwater samples.

Concentrations of metals tended to be higher in stormwater than in subsurface water samples. Concentrations in subsurface samples were variable and generally stable or decreasing. Exceptions are increasing trends of copper in lysimeter samples collected at the Sun Valley site that could be associated with infiltration of storm water with relatively higher concentrations of copper. Most inorganic groundwater quality constituents do not show clear trends or show decreasing concentrations over the study period. In only one instance, involving low concentrations of nitrate, did concentrations of a constituent show a statistically significant, although slight, increase. Groundwater quality data from the shallow groundwater sites show groundwater quality improvement (decreasing salt concentrations) potentially associated with dilution by infiltrating stormwater.

At the non-industrial sites the concentrations of general monitoring parameters such as TDS and chloride tended to be less than or similar to concentrations in lysimeter and groundwater samples. This suggests that the infiltration of stormwater is not likely to have a significant negative impact to groundwater from these constituents. At the Veterans Park site, concentrations of TDS, nitrate, chloride, and other salts in groundwater samples (including pre-infiltration background samples) was much higher than concentrations in stormwater samples. This result is likely due to historical application of fertilizers. Data collected to date suggest that concentrations of many of these constituents in lysimeter and groundwater samples are decreasing with time, possibly due to dilution by infiltrated stormwater.

Other than acetone, VOCs and SVOCs detected in storm water are different than VOCs detected in subsurface samples. VOCs detected in groundwater samples during the monitoring period were also detected in initial background samples. With the possible exception of occasional low level detections of acetone, VOCs in stormwater do not appear to impact groundwater at all. At the industrial sites, groundwater constituents such as MtBE and chlorinated solvents were present in some lysimeter samples at greater concentrations than present in any stormwater samples. This finding suggests the presence of subsurface contamination prior to stormwater infiltration.

The industrial sites had detections of more organic compounds and higher concentrations of metals than the non-industrial sites. The filtration system in the detention basins at Sun Valley and the Metal Recycler site was somewhat effective at reducing concentrations of certain constituents, particularly the dissolved metals. For example, at the Metal Recycler site, concentrations of dissolved arsenic, copper, chromium VI and lead were lower after filtration. The sedimentation basin at Veterans Park and the soil layers at the other sites would also be expected to reduce concentrations of metals and other solids, although effluent was not analyzed separately to verify this.

Although perchlorate was detected in some stormwater samples, there is no evidence of groundwater degradation by perchlorate from stormwater infiltration during this study. The occurrence of perchlorate in stormwater samples was unexpected, as the focus is typically on subsurface sources of perchlorate contamination. Perchlorate is a salt, which in addition to being a component of solid rocket fuel, is also an ingredient in fireworks and road flares. Other constituents of concern for groundwater (disinfection byproducts, 1,4-Dioxane, PAHs and DBCP) were not detected in stormwater.

Soil samples collected from four of the sites at the conclusion of the study indicated no significant increases in parameters monitored, and in many cases constituent concentrations were reduced.

The concentrations of many constituents vary throughout the sampling period, but there is no apparent pattern that can be tied to effects from infiltration. As stated above, VOCs detected in groundwater are routinely different than those in stormwater. VOCs detected in groundwater samples collected during the storm season were also detected in pre-season background samples, thus they do not appear to be the result of infiltration. Given the depth to groundwater at the two industrial sites and at Broadous, it seems unlikely that constituents introduced into the soil from stormwater infiltration would migrate all the way to the groundwater at a detectable concentration.

Data collected to date indicate that there is no statistically significant degradation of groundwater quality from the infiltration of stormwater-borne constituents. Groundwater quality has generally improved for most constituents at sites with shallow groundwater.

# 6. SUMMARY

## 6.1 Evaluation of Project Success

The data collected during this study show no immediate impacts, and no apparent trends to indicate that stormwater infiltration will negatively impact groundwater at these sites. While variations in stormwater and groundwater constituents between types of land use were apparent, they may not be a barrier to infiltration. Filtration methods employed at the industrial sites seemed to be effective at removing certain constituents prior to entering the infiltration system, which may make infiltration more feasible at these more contaminated sites. However, site characterization of surface and soil constituents at industrial sites should be conducted prior to implementing infiltration strategies.

Overall the goals of our Phase II study have been met. The specific goals of Phase II were to assess the cumulative impact of infiltration on soil and groundwater, and evaluate the effects of different land uses on constituent types and concentrations. While we see the value in long-term monitoring to better characterize these issues, the data so far have shown positive results for infiltration potential.

## 6.2 Next Steps

### 6.2.1 Long-term Monitoring Program

While the data collected during this program do provide significant information, monitoring will continue in order to better assess the cumulative effects of infiltration. A reduced program of subsurface monitoring is under currently development. This program will likely include annual or bi-annual monitoring of lysimeters and groundwater wells at four or five sites. No stormwater samples will be collected, as surface runoff quality has been well-characterized at these sites. Monitoring will be scheduled after significant storm events and late in the storm season, to ensure that infiltration to the deepest lysimeters has occurred. The analytical suite will be reduced but should include metals, general parameters, some organics, and perchlorate. We expect to continue monitoring for at least two additional years, and possibly longer if funding is available.

### 6.2.2 Phase III Work Plan

Infiltration is not the only means of addressing water supply and water quality issues. We believe that an integrated, comprehensive approach to water management is necessary to maximize efficient use of our water resources. Thus the third phase of the study will incorporate demonstration projects on a neighborhood scale. We propose to retrofit one or more small neighborhoods with state of the art Best Management Practices to address stormwater infiltration as well as water conservation, pollution reduction and treatment, flooding, and habitat and stream restoration. Specific techniques will depend upon the sites selected, but may include conversion to native drought-tolerant landscapes, use of irrigation controllers, facilities to capture runoff for infiltration and/or reuse, restoring buried stream channels, and adding green space and habitat areas. The demonstration projects will be monitored for water quality as well as for reduction of runoff and water use, changes in property values, and other potential benefits. These neighborhood projects will provide real-world models of addressing existing infrastructure and will serve to integrate many on-going efforts in the region to address flood management, water quality, water supply and environmental restoration. Our goal is to demonstrate how these approaches can be applied on a regional scale in Southern California as well as in other geographic regions.

In addition to the demonstration project, we are assessing the overall feasibility of utilizing infiltration techniques to capture stormwater for groundwater recharge. The Bureau of Reclamation is currently developing a groundwater augmentation model to predict the amount of additional water that could be available for deep percolation if infiltration is increased. They are also developing a regional cost and benefit assessment to determine the real cost of this new water supply. Researchers at UC Riverside are assessing costs on a site-specific scale. The long-term goal of this project is a regional strategy for implementation.

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A005617

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# 8. APPENDICES

Appendix A Site Location Maps
Appendix B Analytical List

On cd:
Appendix C Complete Stormwater, Lysimeter, and Groundwater Water Quality Results.
Appendix D Comparative Water Quality Results
Appendix E Soil Analytical Results
Appendix F Time-Concentration Charts and Results of Trend Analysis
Appendix G Depth-Concentration Charts
Appendix H Boring logs
Appendix I Groundwater Hydrographs

## Appendix A. Site Location Maps

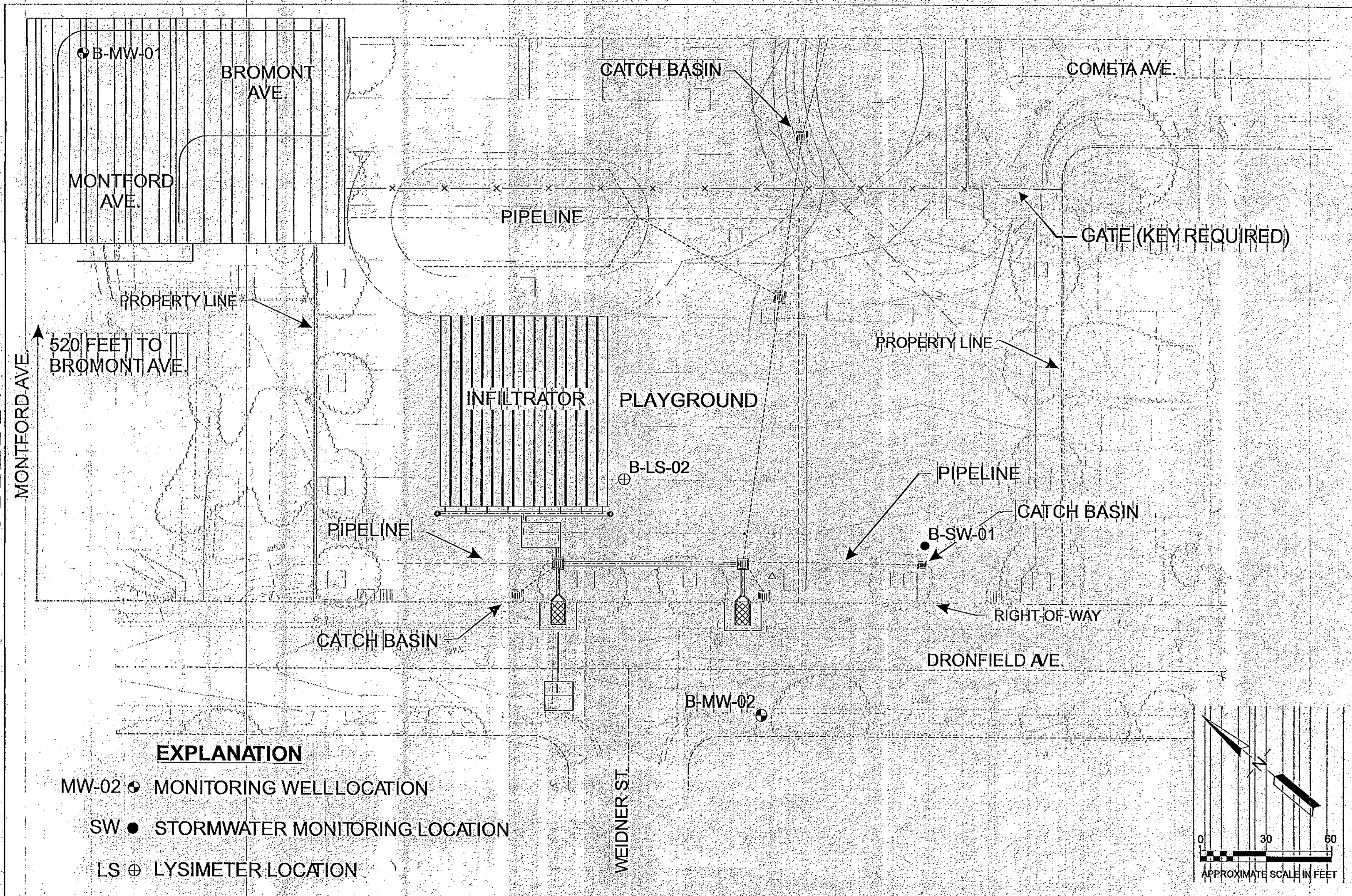
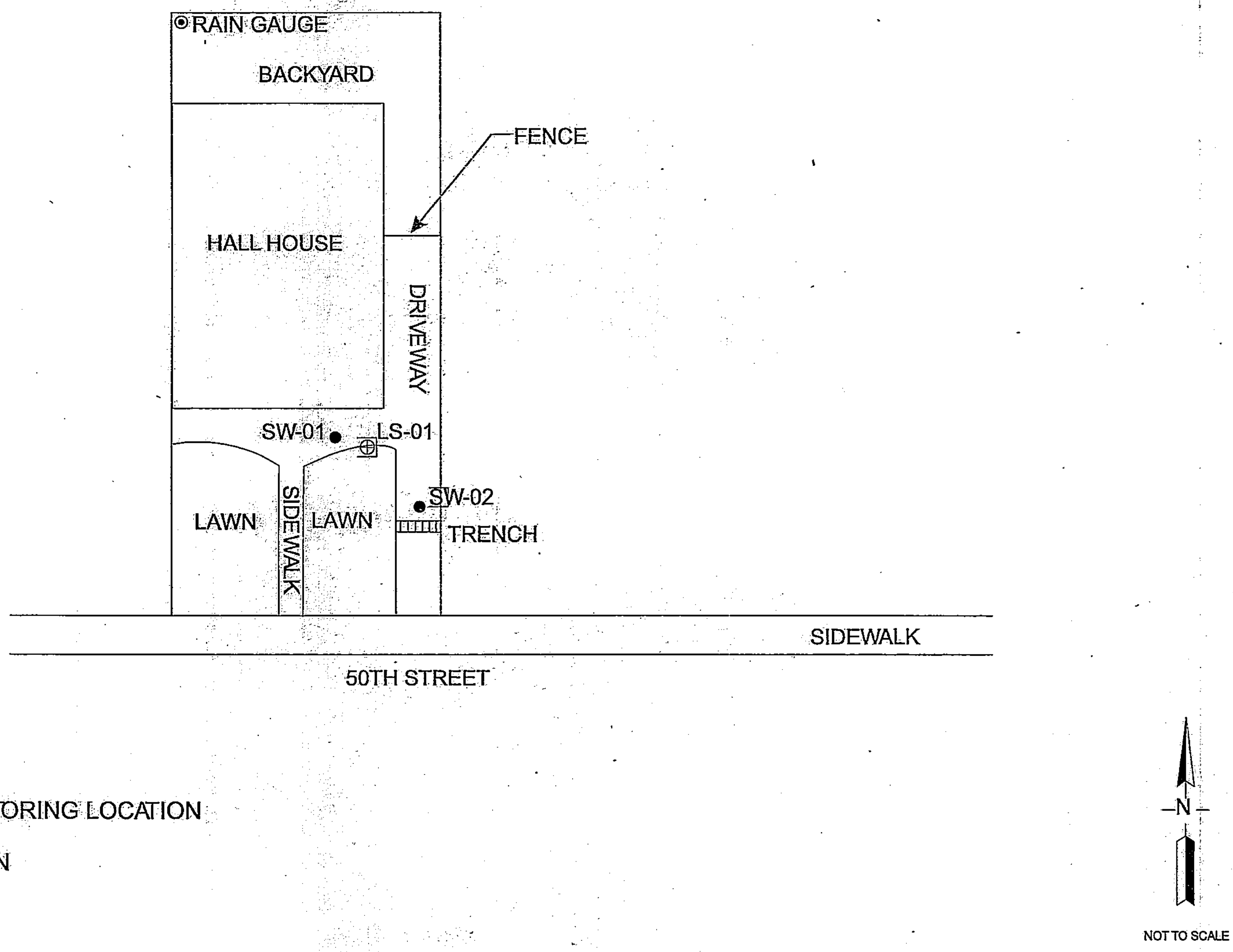



FIGURE A-1
INFILTRATION AND BMP MONITORING SYSTEM - BROADUS SCHOOL SITE

A005621




**EXPLANATION**

SW-01 ● STORMWATER MONITORING LOCATION

LS-01 ⊕ LYSIMETER LOCATION

FIGURE A-2
MONITORING LOCATION MAP - HALL HOUSE

A005622

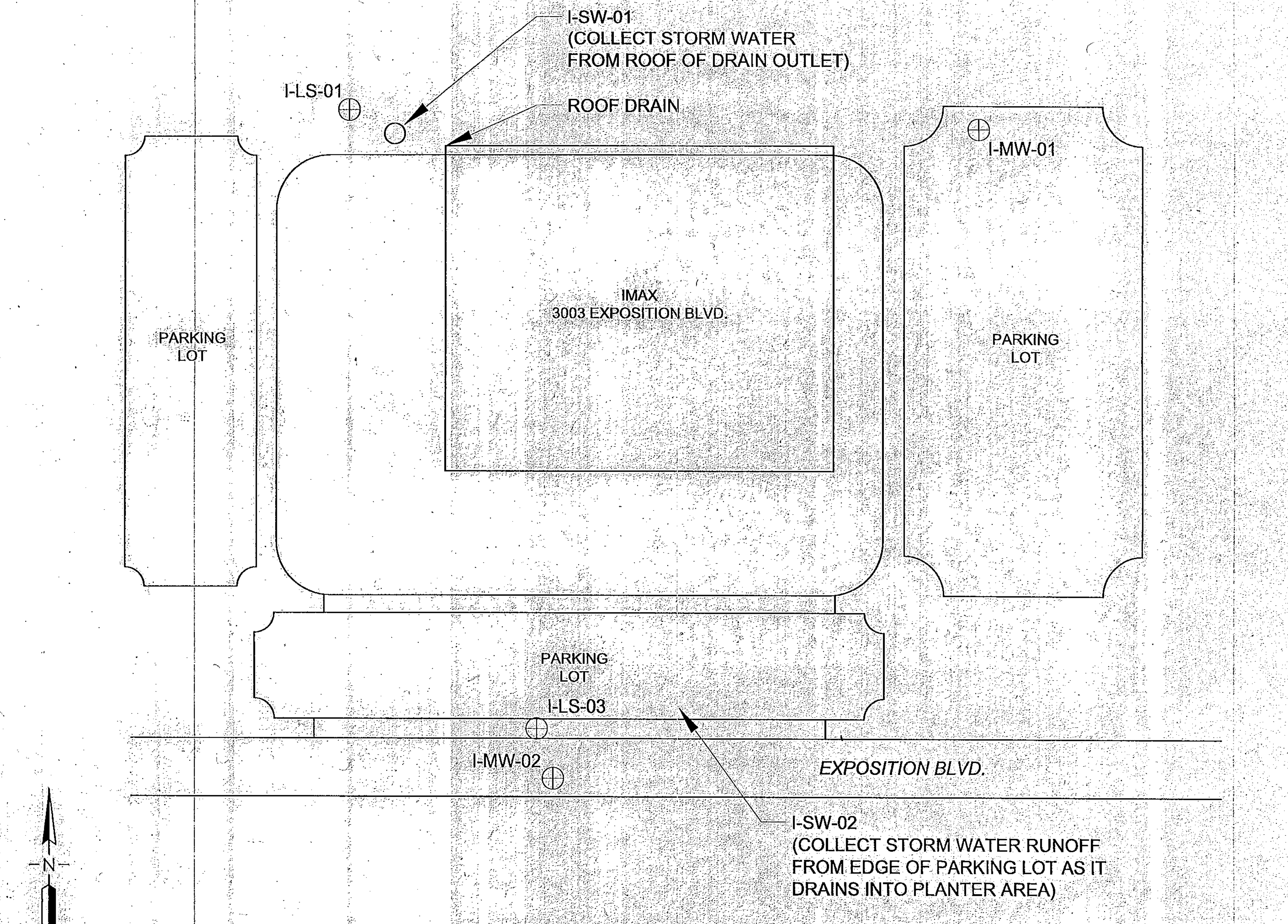



FIGURE A-3
MONITORING LOCATION MAP - IMAX BUILDING

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A005623

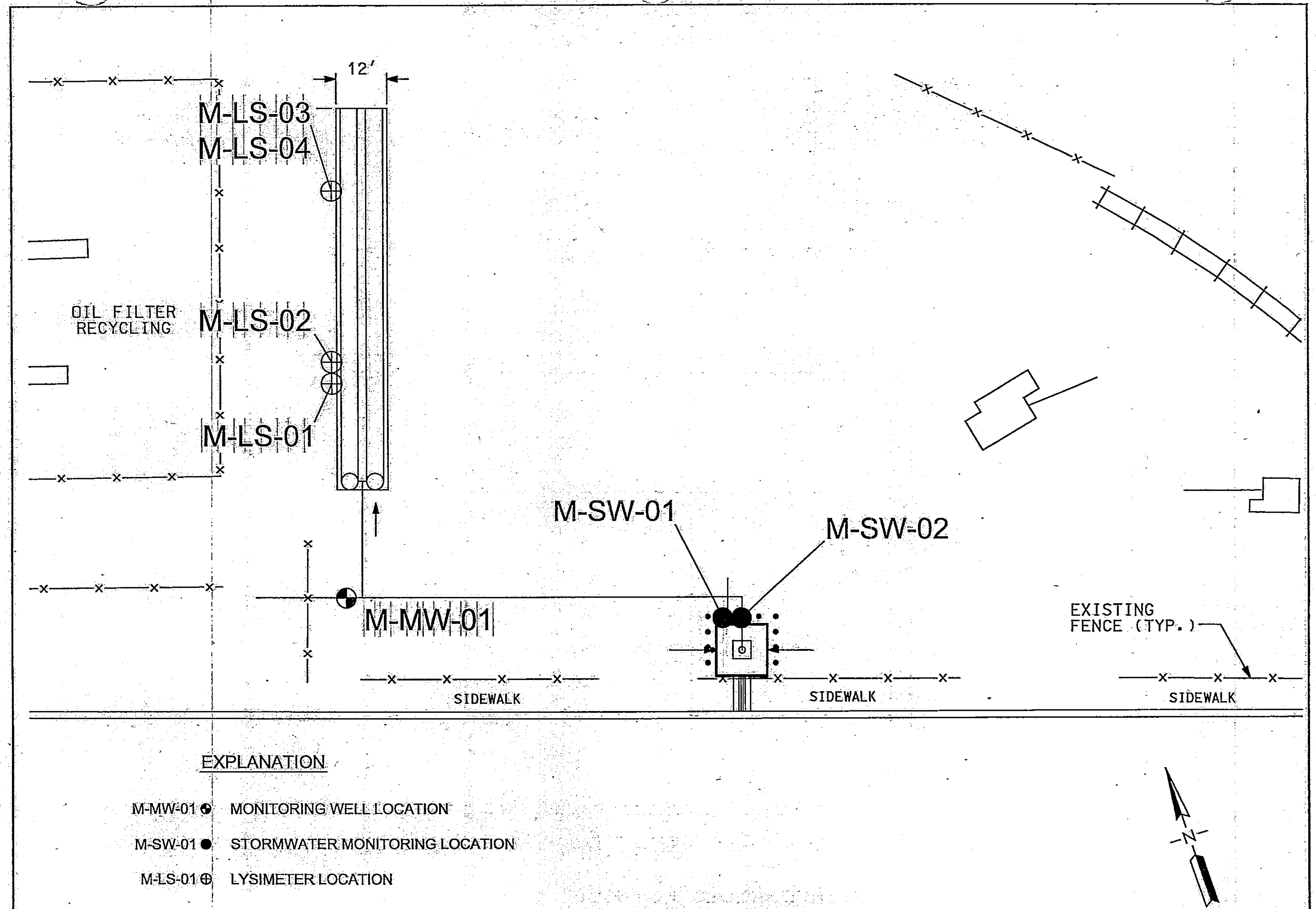


FIGURE A-4
INSTALLED MONITORING SYSTEM - METAL RECYCLER

A005624

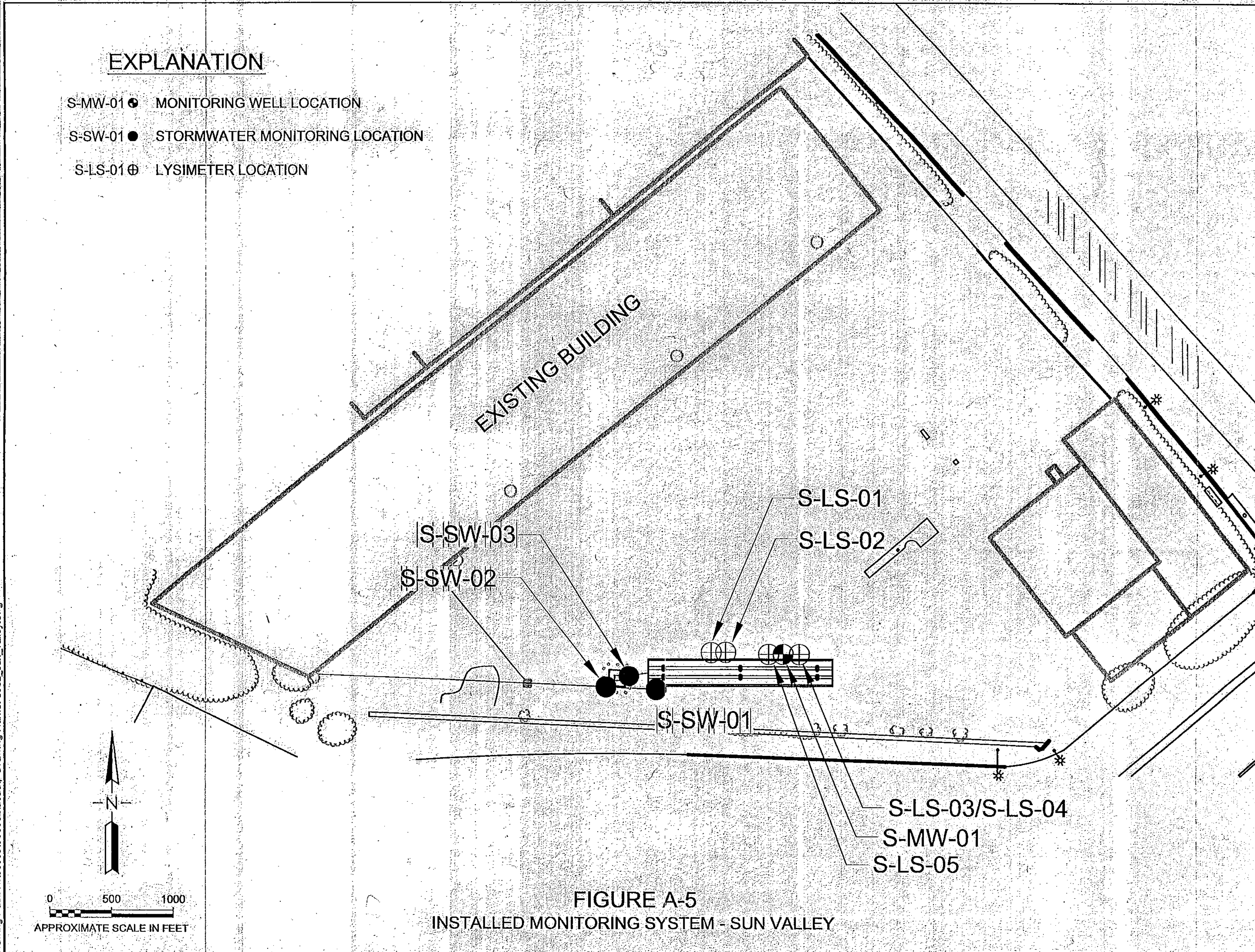


FIGURE A-5
INSTALLED MONITORING SYSTEM - SUN VALLEY

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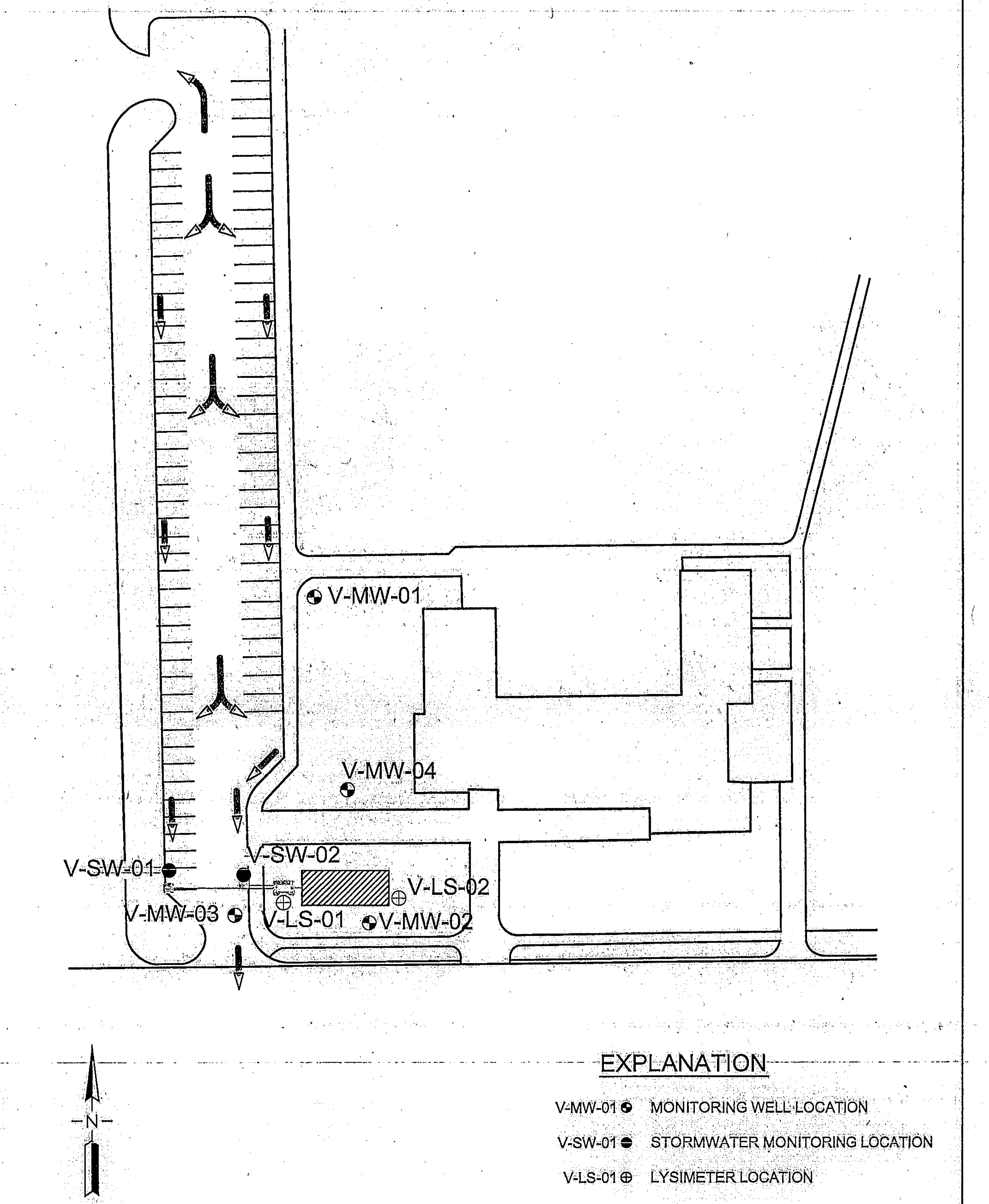
A005625




EXPLANATION

V-MW-01 ⊕ MONITORING WELL LOCATION

V-SW-01 ● STORMWATER MONITORING LOCATION

V-LS-01 ⊕ LYSIMETER LOCATION

FIGURE A-6

INSTALLED MONITORING SYSTEM - VETERANS PARK

Plot Date: 05/11/05 ...23am, Plotted by: dmcgowen
Drawing Path: N:\8000s\008952\acad\, Drawing Name: 8952_veterans_park.dwg

A005626

## Appendix B. Analytical Suite

| Constituent | Detect Limit | Lab Method | Surface & GW | Lysimeter List | Soils |
|---|---|---|---|---|---|
| **General:** | | | | | |
| Alkalinity | 1 mg/L | SM2320B | Y | N | Y |
| Bicarbonate | 1 mg/L | SM2320B | Y | N | Y |
| Bromide | 0.1 mg/L | EPA 300 | Y | Y | Y |
| Calcium | 0.1 mg/L | EPA 200.7 | Y | N | Y |
| Carbonate | 1 mg/L | SM2320B | Y | N | Y |
| Chloride | 1 mg/L | EPA 300.0 | Y | Y | Y |
| COD | 5 mg/L | EPA 410.4 | Y | Y | Y |
| Fluoride | 0.1 mg/L | EPA 340.2 | Y | N | Y |
| Hardness | 2 mg/L | EPA 130.2 | Y | N | N |
| Hydroxide | 1 mg/L | SM2320B | Y | N | Y |
| Magnesium | 0.1 mg/L | EPA 200.7 | Y | N | Y |
| MBAS | 0.1 mg/L | EPA 425.1 | Y | N | Y |
| Nitrate as N | 0.1 mg/L | EPA 300 | Y | Y | Y |
| Nitrite as N | 0.1 mg/L | EPA 300 | Y | Y | Y |
| Total Organic Carbon | 0.5 mg/L | EPA 415.1 | Y | Y | Y |
| Dissolved Organic Carbon | 0.5 mg/L | EPA 415.1 | Y | N | N |
| Organic N | 0.5 mg/L | SM4500NorgE | Y | Y | Y |
| NH3 | 0.1 mg/L | EPA 350.2 | Y | Y | Y |
| pH | na | EPA 150.1 | Y | field | Y |
| Phosphorous - total | 0.03 mg/L | EPA 365.3 | Y | Y | Y |
| Phosphorous - dissolved | 0.03 mg/L | EPA 365.3 | Y | N | N |
| Potassium | 0.5 mg/L | EPA 200.7 | Y | N | Y |
| Sodium | 0.5 mg/L | EPA 200.7 | Y | N | Y |
| Specific Conductance | 4 umho/cm | EPA 120.1 | Y | field | N |
| Sulfate | 1 mg/L | EPA 300 | Y | Y | Y |
| TDS | 1 mg/L | EPA 160.1 | Y | Y | N |
| TSS | 1 mg/L | EPA 160.2 | Y | N | N |
| Turbidity | 0.05 NTU | EPA 180.1 | Y | N | N |
| **Metals (total & dissolved)** | | | | | total |
| Aluminum | 50 µg/L | EPA 200.8 | Y | Y | Y |
| Antimony | 1 µg/L | EPA 200.8 | Y | Y | Y |
| Arsenic | 2 µg/L | EPA 200.8 | Y | Y | Y |
| Barium | 1 µg/L | EPA 200.8 | Y | Y | Y |
| Beryllium | 1 µg/L | EPA 200.8 | Y | Y | Y |
| Boron | 50 µg/L | EPA 200.8 | Y | Y | Y |
| Cadmium | 0.2 µg/L | EPA 200.8 | Y | Y | Y |
| Chromium | 1 µg/L | EPA 200.8 | Y | Y | Y |
| Chromium VI | 0.2 µg/L | EPA 218.6 | Y | Y | Y |
| Cobalt | 1 µg/L | EPA 200.8 | Y | Y | Y |
| Copper | 1 µg/L | EPA 200.8 | Y | Y | Y |
| Iron | 100 µg/L | EPA 200.8 | Y | Y | Y |
| Lead | 0.5 µg/L | EPA 200.8 | Y | Y | Y |

| Constituent | Detect Limit | Lab Method | Surface & GW | Lysimeter List | Soils |
|---|---|---|---|---|---|
| Manganese | 1 µg/L | EPA 200.8 | Y | Y | Y |
| Mercury | 0.1 µg/L | EPA 7470.A | Y | N | Y |
| Molybdenum | 1 µg/L | EPA 200.8 | Y | Y | Y |
| Nickel | 1 µg/L | EPA 200.8 | Y | Y | Y |
| Selenium | 1 µg/L | EPA 200.8 | Y | Y | Y |
| Silver | 1 µg/L | EPA 200.8 | Y | Y | Y |
| Thallium | 1 µg/L | EPA 200.8 | Y | Y | Y |
| Zinc | 5 µg/L | EPA 200.8 | Y | Y | Y |
| **Volatile Organic Compounds** (full suite) | | | Y | Y | EPA 8260 |
| Methyl Bromide | 0.5 µg/L | EPA 524.2 | inc | inc | inc |
| BTEX | 0.5 µg/L | EPA 524.2 | inc | inc | inc |
| MtBE | 1 µg/L | EPA 524.2 | inc | inc | inc |
| DIPE | 2 µg/L | EPA 524.2 | inc | inc | inc |
| ETBE | 2 µg/L | EPA 524.2 | inc | inc | inc |
| TAME | 2 µg/L | EPA 524.2 | inc | inc | inc |
| TBA | 10 µg/L | EPA 524.2 | inc | inc | inc |
| Ethanol | 100 µg/L | EPA 524.2 | inc | inc | inc |
| TCE | 0.5 µg/L | EPA 524.2 | inc | inc | inc |
| PCE | 0.5 µg/L | EPA 524.2 | inc | inc | inc |
| Disinfection Byproducts (THMs) | 0.5 µg/L | EPA 524.2 | inc | inc | inc |
| 1,2,3-TCP | 0.005 µg/L | GC/MS Isotope Dilution | Y (1 time) | N | Inc |
| Trip blanks | N/A | upon request | | | |
| **Other** | | | | | |
| Oil and Grease | 1 mg/L | EPA 1664 | Y | Y | Y |
| Perchlorate | 2 µg/L | EPA 314 | Y | N | Y |
| Semi-volatile Organics (full suite) | 5-50 µg/L | EPA 625/8270C | Y | N | Y |
| NDMA | .002 µg/L | EPA 1625mod | Y | N | N |
| Round-up (Glyphosate) | 10 µg/L | EPA 547 | Y | N | Y |
| 1,4 Dioxane | 2µg/L | GC/MS Isotope Dilution | Y | N | N |
| DBCP | 0.02 µg/L | EPA 504.1 | Y | N | Y (8260) |
| **Biological:** | | | | | |
| HPC | <1 CFU/mL | SMEWW 20th | Y | Y | Y |
| Total coliforms | 1.1 MPN/100ml | SMEWW 20th | Y | Y | Y |
| Fecal coliform | 1.1 MPN/100ml | SMEWW 20th | Y | Y | Y |
| E. coli | 1.1 MPN/100ml | SMEWW 19th | Y | Y | Y |

# The Washington Water RESOURCE

*The quarterly report of the Center for Urban Water Resources Management*

Volume 12 ❖ Number 4 ❖ Fall 2001

**CONTENTS**



## Message from the Director

For the second year running the Center has joined forces with our sister center in Forestry and Fisheries, the Center for Streamside Studies, and will co-host the next presentation of research results from the two centers on **Wednesday, February 6, 2002** in the HUB West Ballroom on the University of Washington campus. This is a full-day affair that hosted more than 300 people last year and is still provided at no cost to the public and professional community. The preliminary schedule of the day is given below; additional information will be posted on the CSS web site, http://depts.washington.edu/cssuw/, as the date gets closer.

Our two centers continue to move closer to joint operation in many other capacities. The Annual Review is one of the most visible expressions of that trend, but we are also working to integrate research and educational efforts in order to dissolve the arbitrary (and generally unproductive) divisions that can be perceived between "urban" and "forestry" approaches to water-resource issues.

In addition to planning for the Annual Review, the end-of-year season also brings us to the time that Center subscription renewals for 2002 will be sent out, planned for mid-January. Subscriptions cover the cost of the newsletter and help support many of the ongoing, cooperative functions of the Center as well. A final upcoming year of support from the College of Forest Resources continues to allow us to maintain the same subscription rates that have been in effect since the Center began in 1990. I also remind you that all are welcome to add additional recipients of the newsletter to your subscription without charge, because our interests are all best served through the broadest distribution of information.

After a flurry of activity up until the end of the summer, the 2001 Stream Temperature Survey has reached an impasse in data analysis, only a few short days shy of completion. We have 485 new temperature measurements on nearly 100 individual streams, ranging from 9 to 24 °C, with over 50 replicate measurements (same site, different times and/or different people) to evaluate the overall quality of the data set. The data should be posted on the Center's web site by early 2002, but if you have need or interest in it earlier, feel free to email us for an advance copy. Many thanks, as always, for the nearly 100 volunteers this year that made the work possible.

*Continued on page 2*

MESSAGE FROM THE DIRECTOR
(from page 1)

**Preliminary Schedule, Annual Review of Research for the Center for Urban Water Resources Management and the Center for Streamside Studies**

Wednesday, February 6, 2000, 8:30-4:15, HUB West Ballroom, University of Washington Campus, Seattle.

8:30 **Opening remarks**

8:45 *Why do they care? Landscape management for nonpoint source pollution by small parcel owners*
Kathleen L. Wolf

9:00 *A study of periphyton induced pH spikes on the White River, Washington*
Derek Stuart

9:15 *Regional stream temperature estimation using thermal infrared remote sensing and ground measurements*
Keith Cherkauer

9:30 *Heavy metal contamination from abandoned mines and its effect on organisms in the Methow River in Okanogan County, Washington*
Dan Peplow

9:45 *Land management for nonpoint source pollution: Methods and motivations*
Clare M. Ryan

10:00 **Break and Poster Session**

10:15 *A daily time series analysis of urbanization effects on stream phosphorus concentrations and transport in the greater Seattle region*
Sara Stanley

10:30 *Urbanization impacts on stream nutrient concentrations*
Mike Brett

10:45 *Opportunities for benign hydrologic design in urban areas*
Rich Horner

11:00 *Assessing the availability of spawning gravel in an urban creek system*
Chase Barton

11:15 *Variability of hyporheic flows in Puget Sound lowland streams*
Cathy Reidy

11:30 *Protecting physical stream channels with classic stormwater mitigation: Fact or fantasy*
Karen Comings

11:45 **Lunch Break and Poster Session—dessert provided**

1:15 *The development and organization of old growth river valley forests*
Kevin Fetherston

1:30 *Spawning salmon as forest fertilizer: effects on riparian structure and composition*
Krista Bartz

1:45 *When is hydrologic maturity: Inferring temporal change in hydrologic response from paired streamflow data*
Finn Krogstad

2:00 *Short-term suspended-solid concentrations from stream crossing restoration work in the Clearwater NF, Idaho*
Tim Brown

2:15 *Ten years after: Evaluation of restoration efforts*
Mark Muir

Continued on page 3

MESSAGE FROM THE DIRECTOR
(from page 2)

2:30 **Break and Poster Session**

2:45 *Flow regimes of charr spawning streams: Implications for bedload scour during the incubation period*
Jeff Shellberg

3:00 *Multi-scale prioritization of riparian habitat restoration and preservation*
Raymond Timm

3:15 *Nonmigratory coastal cutthroat trout: Evidence for restricted gene flow among neighboring creeks*
Josh Latterell

3:30 *The phylogeny of behaviour: Salmoninae spawning patterns*
Manu Estevé

3:45 *Changing temperature regimes and the spawning timing of coho and chinook salmon*
Tom Quinn

4:00 **Closing Remarks**

Posters:

- Riparian canopy cover and its effects on stream temperature in eastern Washington (Ashley Adams)
- Microbial production in the hyporheic zone of a coastal floodplain river (Sandra Clinton)
- The effect of marine-derived nutrients on secondary production of macroinvertebrates in a salmon spawning stream (Jon Honea)
- Short-term tree fall patterns from riparian buffers (Mike Liquori)
- Impacts of riparian vegetation on in-stream ecosystems and nutrient dynamics (Carol Volk)
- Ecological role of estuarine large woody debris supporting juvenile Pacific salmon (Ali Wick)
- Evaluation of North Creek channel conditions. ❖

*The Washington Water Resource* is the quarterly publication of the Center for Urban Water Resources Management at the Department of Civil and Environmental Engineering, University of Washington, Box 352700, Seattle, WA 98195.

***Web address:***
**http://depts.washington.edu/cuwrm/**

# Hydrologic Trends and Hydrologic Monitoring in Urbanizing Streams of Western Washington

*Christopher P. Konrad, U. S. Geological Survey, Water Resources Division, and Derek B. Booth, University of Washington, Center for Urban Water Resources Management*

## 1. INTRODUCTION

This study was initiated to explore the use of specifically *hydrologic* monitoring elements to evaluate the condition of lowland watersheds and the effectiveness of hydrologic mitigation (typically, detention ponds). Its specific purpose is to develop and make recommendations for a method to measure changes to the hydrologic regime of streams in urbanizing watersheds that are relevant to the ecological health of those streams, and to assess the practicalities, including the sensitivity and the minimum duration of monitoring, of implementing such a method. This work was based on hydrologic analyses first published in the Fall 2000 issue of the Newsletter, now focused to help answer the question, "Is the hydrologic regime of this stream improving or declining over time?"

### 1.1. Overview of the Effects of Urban Development

When vegetation is cleared from hillslopes in a stream basin, the land surface is graded, and building and roads are constructed, the resulting urban landscape causes a variety of changes in the downstream channels. These development activities generally reduce the storage of stormwater on hillslopes, and they shorten the time required for stormwater to travel over and through a hillslope to a stream. As a result, some of the most significant characteristics unique to urban, or urbanizing, streams are their increased peak discharge rates and their rapid rise and recession of storm flows. These hydrologic consequences of urban development can cause both social and ecological damage, including increased flooding and bank erosion, increased contaminant transport, and changes to instream habitat. Yet the "classic" metrics of urban-induced hydrologic change, such as the fractional increase in the 2-year discharge, are poorly suited to characterize the magnitude of such changes, because they do not facilitate comparisons between basins and they do not have any demonstrable (or even plausible) linkage with other important instream conditions, particularly biological health.

### 1.2. Stream Flow Variability

The hydrologic effects of urban development, and the stormwater management activities intended to mitigate those effects, are not easily evaluated because streamflow varies over time. Although this short-term variability confounds monitoring it may be of little direct ecological significance, because biological conditions in streams re-establish quickly, often within months, after hydrologic disturbances such as floods and droughts (Boulton et al., 1992; Bayley and Osborne, 1993; Jones et al., 1995). In contrast, changes in stream flow patterns over annual or multiple-year time scales are likely to have a persistent influence on the biological conditions of urban streams (Poff et al., 1997).

Thus the temporal variability of streamflow at the scale of both storms and seasons, and the resilience of biological systems to these short-term changes, precludes the use of short-term streamflow patterns for monitoring anthropogenic effects. Even annual streamflow statistics, such as maximum annual peak flow or summer low flow, may vary by as much as an order of magnitude from year-to-year even without changes in land use, because of broad multi-year weather patterns such as El Nino-Southern Oscillation and the Pacific Decadal Oscillation. In consequence, anthropogenic changes in streamflow patterns are only likely to be detected where the change is large relative to the variation caused by climatic conditions. The hydrologic effects of urban development may be evident only for streams with extensive urban development and hydrologic data that span a relatively long period of time.

## 2. METHODS

### 2.1. Streamflow Metrics

Existing stream-gage records can be used to determine exactly what streamflow patterns are most expressive of anthropogenic change, to evaluate the improvement in statistical confidence of using records of progressively longer duration, and to determine the minimum length of record that is likely to yield any useful conclusions whatever. Beginning with the general, long-understood effects of urbanization on watershed hydrology (Hollis, 1975; Leopold, 1968; Booth 1991) and our expectation of the hydrologic determinants of ecological health, we investigated four metrics from existing gage records that characterize a range of streamflow patterns: the mean discharge rate, the fraction of the year that the mean discharge rate is exceeded, the minimum 7-day mean discharge rate, and the maximum (instantaneous) discharge rate. They are each described below:

1. *The mean discharge rate* ($Q_{mean}$) provides a broad measure of flow in a stream. The magnitude of $Q_{mean}$ in western Washington streams is typical of periods of winter baseflow and stormflow recession. Urban development is not

| | 1995 Land use | Drainage area (km²) | Period of record | |
|---|---|---|---|---|
| | | | *Daily values* | *Max values* |
| **Leach** | Urban | 12 | 1958-1985<br>1989-1998 | 1958-1998 |
| **Juanita** | Urban | 17 | 1964-1990 | 1964-1991 |
| **Huge** | Rural | 17 | 1947-1969<br>1978-1998 | 1948-1998 |
| **Swamp** | Suburban | 25 | 1964-1990 | 1964-1990 |
| **Mercer** | Urban | 31 | 1956-1998 | 1956-1998 |
| | | | 1965-1971<br>1989-1990<br>1993-1998 | |
| **Big Beef** | Rural | 35 | 1970-1981<br>1996-1999 | 1970-1981<br>1996-2000 |
| **Newaukum** | Rural | 70 | 1945-1950<br>1953-1998 | 1945-1998 |
| **Issaquah** | Rural | 145 | 1964-1998 | 1964-1998 |
| **Soos** | Suburban | 171 | 1961-1999 | 1961-1999 |

**Table 1.**
Western Washington Streams Used in this Analysis

*Continued on page 5*

*HYDROLOGIC TRENDS AND HYDROLOGIC MONITORING IN URBANIZING STREAMS OF WESTERN WASHINGTON*
*(from page 4)*

anticipated to have a systematic effect on $Q_{mean}$, unless there is extensive irrigation with water imported from other basins or pumped from aquifers.

2. *The fraction of the year that $Q_{mean}$ is exceeded ($T_{Qmean}$)* is measured by counting the number of days in a given water year (October 1-September 30) that the daily mean discharge rate exceeds that year's overall $Q_{mean}$. $T_{Qmean}$ provides a measure of the relative distribution of stormflow to baseflow in a stream—where peak discharges are large and inter-storm baseflow is low, the classic picture of a "flashy" hydrograph, the large peaks will maintain a relatively high value of $Q_{mean}$ but the hydrograph will spend relatively little time above that value. Thus $T_{Qmean}$ will show high values for streams where baseflow is high and stormflow is subdued, and it is anticipated to decline in streams during periods of urban development as runoff is redistributed from stormflow recession and baseflow to stormflow peaks. $T_{Qmean}$ can also be calculated from shorter unit values (*e.g.*, 15-minute mean discharge), although these results are not likely to differ by more than 0.05 (*i.e.* 5 percent of the year) from the value calculated from mean daily discharges (Konrad, 2000).

3. *The minimum 7-day mean discharge rate ($Q_{min}$)* provides a measure of magnitude of streamflow during summer baseflow conditions. Although a reduction in this metric is an oft-anticipated consequence of urban development, reported data simply do *not* support such a universal assertion. Klein (1979) studied 27 small Maryland watersheds and concluded that baseflow dropped by as much as 90 percent with predominantly impervious land cover. Simmonds and Reynolds (1982) estimated the volume of baseflow as a fraction of total stream flow on a part of Long Island, New York, and found an inverse correlation with the amount of urban development. The greatest change occurred with the construction of both sanitary sewers and storm sewers, which reduced the baseflow proportion from 95 percent to only 20 percent. When septic systems remained in urbanized (storm-sewered) areas, the baseflow proportion dropped but only to 84 percent. Yet in those parts of Long Island where recharge (infiltration) basins are the primary means of stormwater disposal, annual streamflow has actually *increased* by 12 percent (Ku and others, 1992). Similarly, data on the distribution of seasonally dry streams in the Puget Lowland (Booth and Wall, 1998) show no systematic differences in the minimum watershed size of perennial (*i.e.* baseflow-supported) streams draining urban or non-urban landscapes (Konrad, 2000).

4. *The maximum (instantaneous) discharge rate ($Q_{max}$)* in any given year provides a measure of the magnitude of streamflow during large storms. $Q_{max}$ increases in response to urban development in a stream basin, particularly for smaller magnitude events where the increases can be as much as an order of magnitude (Hollis, 1975). More typical increases for less frequent (but more potentially damaging) storms, evaluated most rigorously through the use of continuous hydrologic models (*e.g.*, King County, 1991), show typical two- to three-fold increases following urban development. This is approximately the same range of variability imposed by fluctuation in year-to-year weather conditions, even in the absence of any watershed changes.

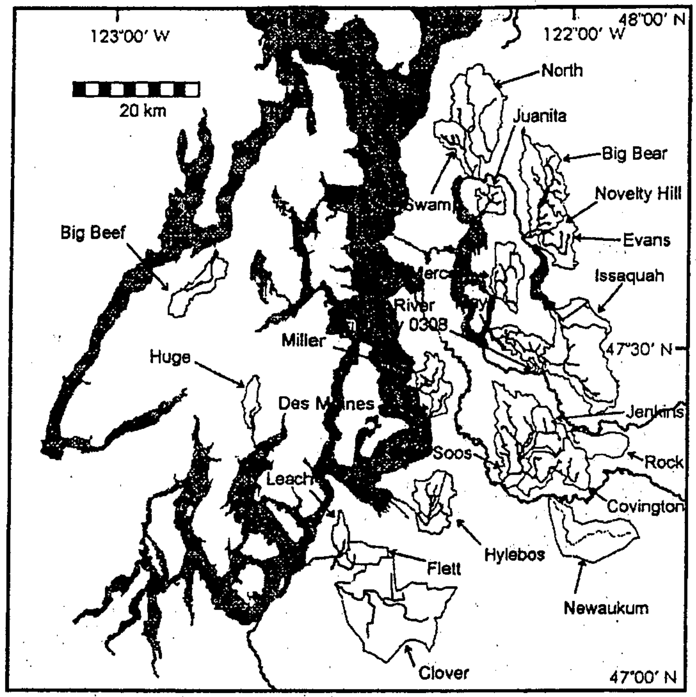



**Figure 1.**
Location of watersheds discussed in text.

## 2.2. Streamflow Records

To evaluate the utility of these four metrics to characterize hydrologic change as a result of urban development, we sought long-term gage records from those watersheds having some level of ongoing urban development. Because the era of active stormwater management in western Washington is less than two decades old, such extensive records are generally limited to those of the U. S. Geological Survey, whose gaging program has generally emphasized large rivers on the nation's waterways.

Despite such limitations, we identified 10 potentially suitable streams in western Washington with gage records spanning at least 20 years (Table 1). We focused on streams with drainage areas less than 200 km² (about 80 mi²) in the Puget Lowland, where most of the urban development in the region has occurred. We excluded larger rivers and mountain streams because none have extensive urban development relative to other land use in their basins. Furthermore, their physiographic differences (*e.g.*, mountain headwaters) and hydrologic differences (because runoff there is generated by snowmelt, and channel routing can be very significant) could influence the annual variation in streamflow statistics such that they would not be comparable to smaller, lowland streams. Land use (*ca.* 1995) in the streams' basins were discriminated as "urban," "suburban," or "rural" based on road density (Konrad, 2000).

## 2.3. Trend Analysis

Trends in the streamflow statistic were evaluated with a two-sided test for correlation between each statistic and time using Kendall's τ correlation coefficient (Helsel and Hersh, 1993, p. 212):

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$$\tau = \frac{2(I-D)}{n(n-1)}$$

where: $I$ is the number of pairs of annual values of a statistic that have an increasing value over time, $D$ is the number of pairs of annual values that have a decreasing value over time, and $n$ is the total number of annual values of the statistic.

The probability of observing the statistic, S = P-M, is used to test the statistical significance of a trend. S-PLUS 2000 (MathSoft, 2000) was used to perform the tests. The statistics were tested for trends over the period of record for each stream.

### 2.4. Error Analysis

Tests for anthropogenic trends in streamflow patterns are likely to produce a relatively high error rate because of the high annual variability in streamflow. Hydrologic trends can emerge over a shorter periods of record that are *not* significant over the total period of record, and thus these are unlikely to be a consequence of urban development (which tends to be monotonic, and permanent, in its effects). These short-term trends are instead a result of climatic conditions that persist for a few years to a decade; if mistakenly identified as a "consequence of urbanization" they would represent Type I statistical errors (false positives). Alternatively, measured hydrologic change over a relatively short period may not be statistically significant, even though a significant trend did exist over the entire period of record. In such cases, a statistical test would not recognize the importance of the short-term change and so produce a Type II error (false negative).

The error rates of trend tests for each individual stream were analyzed by comparing the results of trend tests for selected intervals to the results of the test over the whole period of record. A sensitivity analysis was also performed to assess the influence of the streamflow record length on error rates. To accomplish this, Kendall's t test was applied to 5-, 10-, and 20-year periods of record. Five-year trends were analyzed for the periods beginning in 1960, 1965, 1970, 1975, 1980, 1985, and 1994. Ten-year trends were analyzed for periods beginning in 1960, 1965, 1970, 1975, 1980, and 1985. Twenty-year trends were analyzed for the periods beginning in 1960, 1965, and 1970 (although data were not available for all periods in all streams). Type I errors (false positives) were identified for any stream that had a statistically significant trend over the 5-, 10-, and 20-year period but did not have a trend, or had a trend of the opposite direction, over the whole period of record. Type II errors (false negatives) were identified for any stream that showed no statistically significant trends during any of the 5-, 10-, and 20-year periods but did have a trend over the whole period of record.

Step-trends, or differences in the value of a statistic between two multiple-year periods, were analyzed with Student's t-test (Helsel and Hirsh, 1993, p. 124). Student's t-test can only be applied to groups of normally distributed variables. By inspection we judged that annual values of $Q_{mean}$, $T_{Qmean}$, and $Q_{min}$ are normally distributed and performed a logarithmic transformation of $Q_{max}$ before applying the test.

One-sided t-tests were employed to evaluate the likelihood of Type I errors (test shows a significant difference in the value of the statistic between two time periods in a stream where there was no trend) and Type II errors (test shows no significant difference between values of a statistic between two time periods in a stream where there was a trend). Five-year and ten-year mean values of the statistics were calculated for consecutive periods and for periods separated by 5 years.

## 3. RESULTS

### 3.1. Trends Over the Period of Record

The results of the tests for trends over the periods of record for all streams using Kendall's t test are provided in Table A1 and graphed in Figures A1 and A2 (included at the end of this report). Although all statistics exhibited trends, only $T_{Qmean}$ and $Q_{max}$ consistently exhibited trends in the three streams with high levels of urban development: Mercer, Juanita, and Leach creeks. $Q_{max}$ increased significantly in all three "urban" streams. $T_{Qmean}$ decreased significantly over time ($p< 0.05$ of no trend) in Mercer and Juanita creeks; Leach Creek (and also Huge Creek, one of the "rural" streams) also had a decreasing trend in $T_{Qmean}$ but it was not statistically significant ($0.05< p < 0.06$ of no trend). None of the "suburban" or other rural streams had significant trends in either $Q_{max}$ or $T_{Qmean}$.

Trends in $Q_{mean}$ and $Q_{min}$ were not consistently observed for either individual streams or the overall groupings of urban, suburban, or rural streams. A significant increase in $Q_{mean}$ was detected in Leach Creek but not in Mercer or Juanita creeks (urban), and significant decreases were detected in Newaukum and Issaquah creeks. Significant increases in $Q_{min}$ were detected in Mercer, Swamp, and Big Beef creeks. Only Issaquah Creek showed a significant decrease in $Q_{min}$, accompanying its unique (at least among this population of streams) decrease in $Q_{mean}$.

### 3.2. Trends Over Shorter Periods

Trends in streamflow statistics over more limited periods (5, 10, and 20 years) were analyzed in Juanita, Mercer, Leach, and Soos creeks using Kendall's t test. Error rates were generally high for all statistics (Table A2). Type I error rates (false positives) were below 50 percent of streams only for trend tests using 20 years of record. Using 20 years of record, the Type I error rates were lowest for tests of $T_{Qmean}$. Type II error rates (false negatives) were above 50 percent for all metrics and all periods, except $T_{Qmean}$ with 10 years of record.

### 3.3. Step Trends

The difference in the value of a statistic between two periods of time was evaluated using Student's t-test (Table A2). The purpose was to evaluate the likelihood of errors in using this approach rather than quantifying the difference in the value of a statistic over time. For two consecutive samples of 5 years, both types of errors are very common. Type I errors range from 40 percent for $Q_{max}$ to 64 percent for $Q_{min}$. Type II errors range from 44 percent for $Q_{min}$ to 83 percent for $T_{Qmean}$.

The likelihood of either Type I or Type II errors generally decreases for larger sample sizes and longer separation of the periods being compared. For two samples of 10 years' duration separated by 10 years (i.e. the full record spans 30 years), the performance improves substantially: probabilities of a Type I error are

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40 percent for $T_{Qmean}$, 8 percent for $Q_{min}$, and 18 percent for $Q_{max}$. The probability of Type II error is 40 percent for $T_{Qmean}$ and 63 percent for $Q_{min}$; no Type II errors occur for $Q_{max}$.

3.4. Same-Period, Between-Watershed Trends

Konrad (2000) explored the values of $T_{Qmean}$ in 23 Puget Lowland watersheds with differing land use over the 10-year interval 1989-1999. As in the present analysis, the fraction of the year that daily mean discharge rate ($Q_{daily}$) exceeded the annual mean discharge rate ($Q_{mean}$) was determined for each year of record for each stream. An average value of $T_{Qmean}$ over this period was then calculated as the average annual fraction that $Q_{daily} > Q_{mean}$. This multi-year averaging precludes this technique as a method of discerning trends over time, but it does demonstrate the responsiveness of the metric to land-use changes.

The decadal-averaged $T_{Qmean}$ generally varied inversely with urban development among Puget Lowland streams. The mean value of $T_{Qmean}$ for WY 1989 through 1998 for 11 urban streams (defined as a road density > 6 km per km$^2$) was 0.29 while it was 0.34 for 12 suburban streams (road density < 6 km per km$^2$). The difference is statistically significant ($p < 0.01$ using Student's t-test of samples with equal variance). "Suburban" streams had values of $T_{Qmean}$ greater than or equal to 0.32 with the exception of Huge Creek. "Urban" streams had values of $T_{Qmean}$ less than or equal to 0.31 with the exception of Clover Creek.

Independent of urban development, larger streams typically have more attenuated stream flow patterns than smaller streams

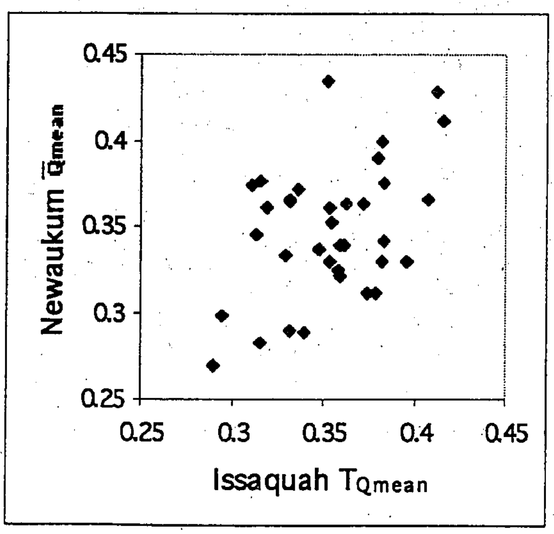


**Figure 2.**
An example of yearly pairs of $T_{Qmean}$ values, plotted here for Issaquah and Newaukum creeks and displaying little relationship between the interannual variability in these two watersheds ($r^2$ = 0.20). Neither watershed has had major, systematic land-use changes over the period of simultaneous gaging (1964-1998), and neither watershed's annual values of $T_{Qmean}$ (Table A1) show any statistically significant trend.

and, as a consequence, higher values of $T_{Qmean}$. The decadal-averaged value of $T_{Qmean}$ for large (drainage greater than 30 km$^2$) streams is 0.35, significantly greater than the mean value of 0.28 for smaller (drainage area < 30 km$^2$) streams. However, an analysis of the decadal-averaged values of $T_{Qmean}$ between urban and suburban streams with drainage areas greater than 20 km$^2$ still indicates significantly lower values in urban streams ($p < 0.01$ based on Student's t-test of samples with unequal variance). Thus, $T_{Qmean}$ is a reliable indicator of urban development but only for comparing watersheds with similar drainage areas (and, presumably, comparable in other physiographic factors as well).

Although statistically significant trends do emerge from ten-year averages, year-to-year variability results in little direct relationship between different watersheds (Figure 2). In consequence, the use of a "reference" watershed to scale the current year's trend of $T_{Qmean}$ in other watersheds, and thus to discern any temporal trends in this parameter with less than the 10- to 20-year record otherwise required (Section 3.2), does not appear warranted.

## 4. DISCUSSION

4.1. Record Length and Trend Identification

The hydrologic effects of urban development in western Washington are manifest as changes in annual stream flow patterns: in particular, $T_{Qmean}$ decreases while $Q_{max}$ increases. These trends are a consequence of the re-distribution of runoff from stormflow recessions and baseflows to stormflow. Trends in the other investigated hydrologic parameters, $Q_{mean}$ and $Q_{min}$, were not consistently observed in urban streams and, in fact, were observed in some suburban and rural streams where watershed-scale land-use changes have not been dramatic. Although urban development may had an influence on $Q_{mean}$ or $Q_{min}$ in some streams, there are no consistent relationships observed.

The natural variability of stream flow is so great that hydrologic trends due to anthropogenic influences are difficult to detect reliably. Particularly for gage records briefer than about two decades, both parametric and nonparametric statistical tests demonstrate relatively high rates of errors. These errors include both the identification of a trend where none exists (Type I error) and *not* identifying a trend where a longer record would show that in fact one *does* exist (Type II error). As a result, any conclusions about hydrologic trends based on short periods of record (<10 to 20 years, at minimum) should be tentative and may not apply to periods before or after the one under investigation.

4.2. Implications for Watershed Monitoring

This analysis of the hydrologic response of watersheds to urbanization holds several implications for watershed monitoring. First, it affirms the underlying premise that evaluating the success of hydrologic mitigation is important—changes are real, and they correlate with (and probably are largely responsible for) well-documented declines in the health of aquatic ecosystems in urban watersheds. Second, hydrologic differences between watersheds can be described by hydrologic metrics, particularly $T_{Qmean}$, that are easily calculated from a daily or hourly discharge record and that capture the influence of urban development far better than traditional measures of streamflow. Finally, the annual variability of rainfall is so great that "trend monitoring" is possible and defensible, but also slow—even the

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large hydrologic influence of urban development will require a gage record that spans 20 years or more in order to recognize trends or to assert their absence.

4.3. Recommendations for Gage Sites

Gage sites suitable for evaluating the hydrologic influence of urban development will have the following general characteristics:

- *Existing or anticipated urban development:* At this time, our analysis does not support the establishment of a network of "control" sites for discerning trends in hydrologic change. Thus sites should be chosen where urban development is anticipated in the contributing watershed.
- *Minimum watershed size:* Perennial stream flow is needed; based on previously compiled data, this requires a contributing watershed area of at least 1 to 10 $km^2$ (0.4-4 $mi^2$) depending on specific conditions. If the site *is* perennial, trends can be identified—there is no other apparent minimum size limitation.
- *Maximum watershed size:* The hydrologic effects of urban development should become increasingly difficult to recognize in progressively larger watersheds. This is due in part because urbanization is less likely to affect large percentages of large watersheds, and in part because the types of hydrologic changes resulting from changes in infiltration and channeled flow become progressively less influential in the hydrographs of increasingly large rivers. Based on our existing data set, the gages at Soos and Issaquah creeks are probably "too large" to be useful for trend determination (171 and 145 $km^2$), Newaukum Creek may be too large (70 $km^2$), and Mercer Creek is clearly *not* too large (31 $km^2$). A maximum size of 40 $km^2$ (16 $mi^2$) is suggested as a working limit, given the present analysis.
- *Length of Record:* Because a minimum of one decade is necessary to detect strong trends and two decades is preferable in most cases, the most suitable sites will be those where a gage record already exists. A discontinued gage site can provide data that is nearly as useful as one in continuous operation, as long as the site had at least several years of previous data and can be reoccupied, and a new regime of data-collection can be initiated.

These four criteria can be readily evaluated from a tabulated list of gage sites and a simple map. One additional set of criteria, however, is warranted as part of making a final selection of gage sites:

- *Watershed sensitivity:* As a generic goal, monitored watersheds should be "sensitive" to the changes imposed by urban development. This sensitivity is expressed by (1) predominant soils, where non-infiltrative deposits or their overlying soil (*e.g.*, glacial till and Alderwood soil) will respond more clearly to any hydrologic expression of urbanization than more infiltrative deposits that may mask the in-channel effects of increased runoff; and (2) channel-network topography and morphometry, where steep and equant (*i.e.* width = length) basins with a high density of channels should be more responsive to changes than flat, elongated basins with a relatively low aggregate length of channels for the size of the watershed. Obvious hydraulic controls, such as a large lake between the area of anticipated development and the gage site, will also compromise sensitivity.

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## APPENDIX

| | | $Q_{mean}$ ($m^3/s$) | $T_{Qmean}$ | $Q_{min}$ ($m^3/s$) | $Q_{max}$ ($m^3/s$) |
|---|---|---|---|---|---|
| Mercer Creek | Years | 43 | 43 | 43 | 43 |
| | Median | 0.63 | 0.29 | 0.17 | 7.9 |
| | Average | 0.64 | 0.29 | 0.17 | 9.49 |
| | CV | 0.21 | 0.14 | 0.23 | 0.57 |
| | p-values for Kendall's t (two-sided) | 0.408 | <0.001(-) | <0.001(+) | <0.001(+) |
| Swamp Creek | Years | 24 | 24 | 24 | 24 |
| | Median | 0.93 | 0.32 | 0.13 | 13.42 |
| | Average | 0.96 | 0.31 | 0.13 | 13.46 |
| | CV | 0.21 | 0.11 | 0.2 | 0.38 |
| | p-values | 0.366 | 0.3 | 0.004(+) | 0.25 |
| Newaukum Creek | Years | 52 | 52 | 52 | 55 |
| | Median | 1.7 | 0.35 | 0.41 | 17.11 |
| | Average | 1.7 | 0.35 | 0.42 | 21.7 |
| | CV | 0.24 | 0.1 | 0.22 | 0.75 |
| | p-values | 0.088(-) | 0.523 | <0.001(-) | 0.0912(-) |
| May Creek | Years | 16 | 16 | 16 | 28 |
| | Median | 0.65 | 0.34 | 0.09 | 6.2 |
| | Average | 0.66 | 0.33 | 0.09 | 8.08 |
| | CV | 0.27 | 0.11 | 0.14 | 0.98 |
| | p-values | 0.32 | 0.55 | 0.45 | 0.55 |
| Leach Creek | Years | 38 | 38 | 38 | 39 |
| | Median | 0.13 | 0.24 | 0.04 | 1.84 |
| | Average | 0.13 | 0.25 | 0.04 | 2.43 |
| | CV | 0.25 | 0.16 | 0.33 | 0.95 |
| | p-values | <0.001(+) | 0.112(-) | 0.333 | <0.001(+) |
| Juanita Creek | Years | 24 | 24 | 24 | 24 |
| | Median | 0.31 | 0.3 | 0.08 | 3.63 |
| | Average | 0.31 | 0.3 | 0.07 | 5.15 |
| | CV | 0.21 | 0.11 | 0.2 | 0.38 |
| | p-values | 0.254 | 0.029(-) | 0.655 | 0.002(+) |
| Big Beef Creek | Years | 16 | 16 | 16 | 16 |
| | Median | 1.28 | 0.28 | 0.1 | 17.8 |
| | Average | 1.22 | 0.28 | 0.1 | 19.72 |
| | CV | 0.35 | 0.21 | 0.21 | 0.56 |
| | p-values | 0.28 | 0.653 | 0.115(+) | 0.418 |
| Huge Creek | Years | 44 | 44 | 44 | 43 |
| | Median | 0.31 | 0.28 | 0.11 | 3.63 |
| | Average | 0.31 | 0.27 | 0.11 | 4.8 |
| | CV | 0.28 | 0.18 | 0.15 | 0.98 |
| | p-values | 0.887 | 0.108(-) | 0.086(-) | 0.645 |
| Soos Creek | Years | 39 | 39 | 39 | 39 |
| | Median | 3.52 | 0.4 | 0.72 | 20.42 |
| | Average | 3.49 | 0.39 | 0.72 | 24.06 |
| | CV | 0.27 | 0.1 | 0.2 | 0.88 |
| | p-values | 0.762 | 0.726 | 0.971 | 0.603 |
| Issaquah Creek | Years | 35 | 35 | 35 | 36 |
| | Median | 3.78 | 0.36 | 0.68 | 46.3 |
| | Average | 3.77 | 0.35 | 0.68 | 45.22 |
| | CV | 0.26 | 0.09 | 0.22 | 0.44 |
| | p-values | 0.063(-) | 0.67 | 0.001(-) | 0.513 |

**Table A1.**
Results of trend analysis over period of record using Kendall's t test; statistically significant values are shaded (with the direction of the trend noted).

| Kendall's t test | $T_{Qmean}$ | $Q_{min}$ | $Q_{max}$ |
|---|---|---|---|
| 5-YEAR PERIODS | | | |
| Type I error | 80% | 60% | 60% |
| Type II error | 100% | 50% | 100% |
| 10-YEAR PERIODS | | | |
| Type I error | 80% | 100% | 100% |
| Type II error | none | 50% | 67% |
| 20-YEAR PERIODS | | | |
| Type I error | 20% | 40% | 40% |
| Type II error | 100% | 50% | 100% |

| Student's t-test | $T_{Qmean}$ | $Q_{min}$ | $Q_{max}$ |
|---|---|---|---|
| Comparison of 5-year means, consecutive periods: | | | |
| Type I error | 33% | 50% | 50% |
| Type II error | 75% | 17% | 100% |
| Comparison of 5-year means separated by 5-year periods: | | | |
| Type I error | 67% | 50% | 25% |
| Type II error | 75% | 17% | 83% |
| Comparison of 10-year means, consecutive periods: | | | |
| Type I error | 67% | 50% | 50% |
| Type II error | 25% | 17% | 83% |
| Comparison of 10-year means separated by 5-year periods: | | | |
| Type I error | 33% | 50% | 50% |
| Type II error | 50% | 33% | 83% |

**Table A2.**
Percentage of streams where trend tests for a subset period produced erroneous results.

- Type I errors: test of a subset period produced false positive compared to the period of record (*i.e.* trend predicted where none exists)
- Type II errors: test of subset period produced false negatives compared to the period of record (*i.e.* no trend recognized where one does exist)

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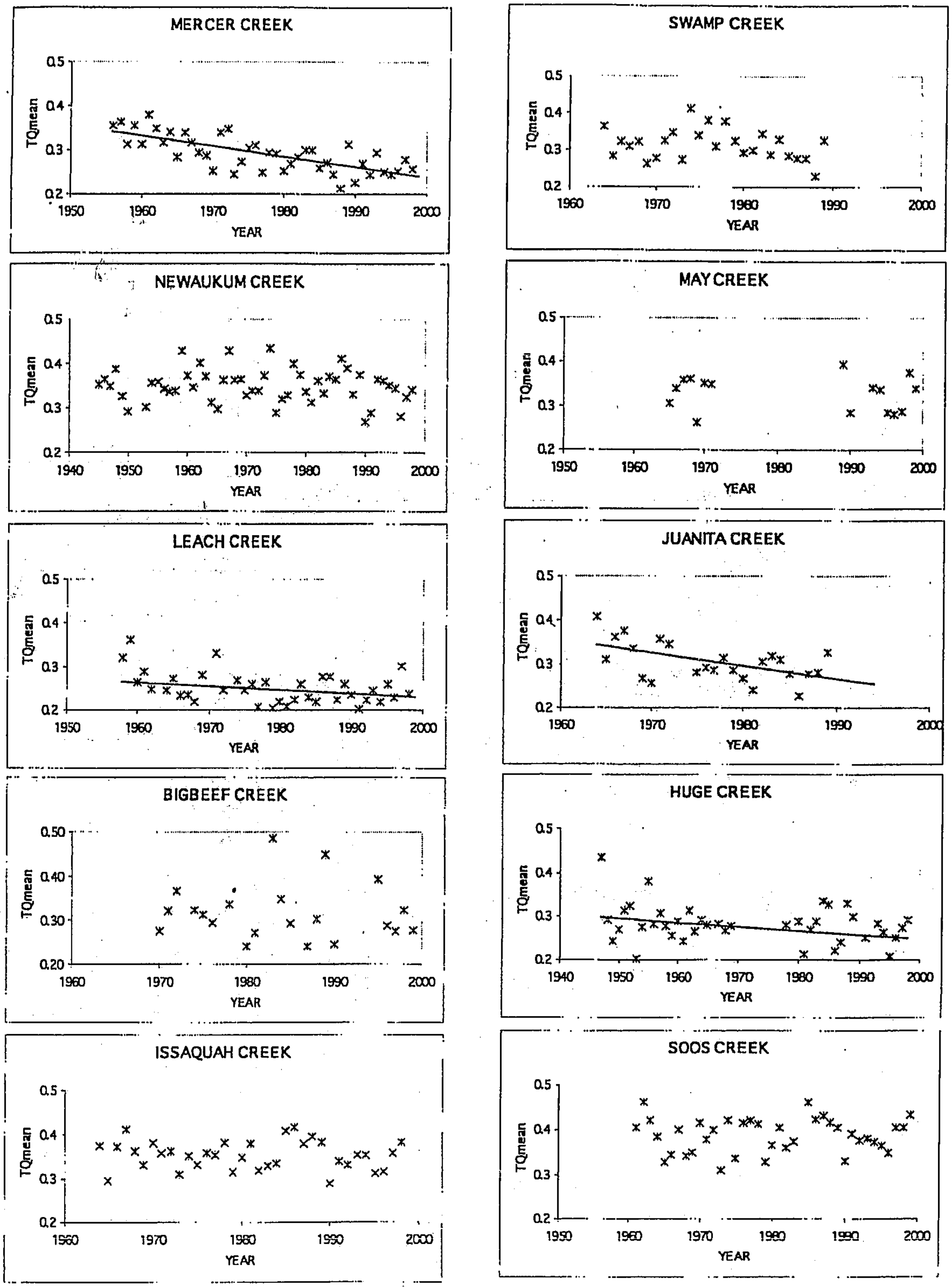


**Figure A1.**

Graphs of all calculated $T_{Qmean}$ values for all streams, all years. Trend lines are plotted only for those with statistical significance (Table A1).

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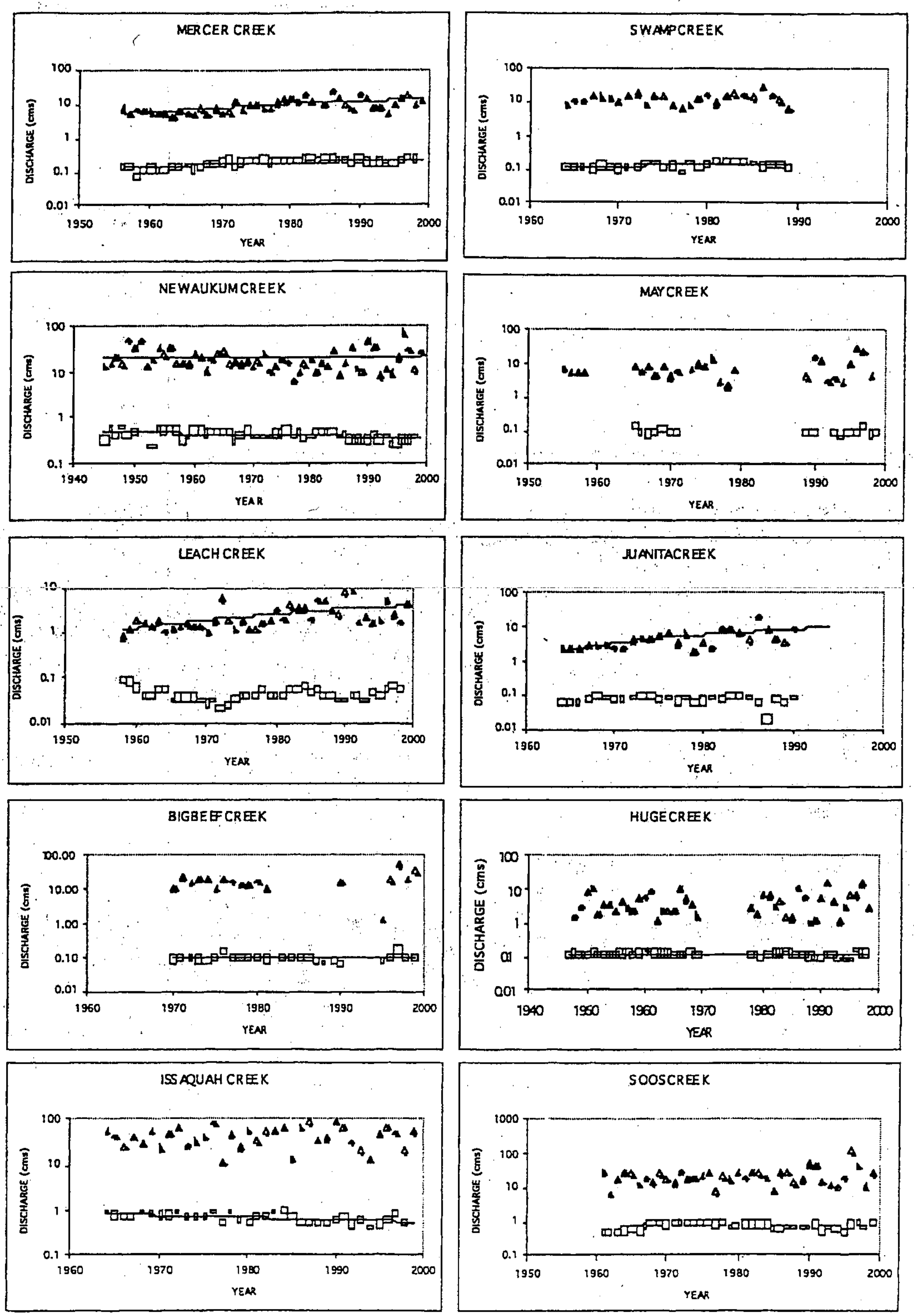


**Figure A2.**
Graphs of all values of $Q_{min}$ (circles) and $Q_{max}$ (triangles) for all streams, all years. Trend lines are plotted only for those with statistical significance (Table A1).

# Publication update of current projects at the Center (with dates of Newsletter articles and available Center publications)

| Project | Newsletter Issue | Center Publication |
|---|---|---|
| LAND COVER AND IMPERVIOUSNESS | | |
| Landsat land cover interpretation | Sp 99, F 00 | CUWRM web rpt. & data |
| Infiltrative parking lot surfaces | W 96, F 96 | K19 |
| The impact of urban patterns on ecosystem dynamics | Su 01 | |
| GEOLOGY AND SOILS | | |
| Puget Lowland geology and geologic hazards | Sp 97, Su 98 | linked web site |
| STREAMS | | |
| Urban stream rehabilitation: | Su 98, Sp 01 | Final report (on web) |
| Riparian buffers in urban watersheds | W 97 | CUWRM web report |
| Effectiveness of LWD in rehabilitation projects | W 00 | K25 |
| Sediment budget of mixed-use watershed | F 99 | K23 |
| Rates of stream channel restabilization | Su 99 | K24 |
| Urbanization effects on stream biology | Sp 00 | K26 |
| Metrics of hydrologic change from urbanization | F 00, F 01 | |
| Urban Planned Development monitoring: | F 99 | CUWRM web report |
| Relationship of turbidity to total suspended solids | | |
| Monitoring of ephemeral streams | | |
| Stream habitat assessment protocols | W 99 | E17 (on CUWRM web) |
| Remote sensing of stream temperature | W 00 | |
| Regional, synchronous stream temperature survey | Su 98, F 98 | CUWRM web data |
| WATER QUALITY/CHEMISTRY | | |
| Water-quality effects of road ditches and swales | F 99, F 00, W 01 | G15 (on CUWRM web) |
| Urban stormwater management evaluation | F 99 | |
| Highway stormwater treatment testing | W 00, F 00 | G14 (on CUWRM web) |
| WATER USE, REUSE, AND GROUNDWATER | | |
| Numerical groundwater modeling of the Duwamish | | CUWRM web report |
| Review of water reuse case studies | Su 01 | L1 (on CUWRM web) |
| On-site runoff mitigation by reuse of rainwater | W 01 | |
| REFERENCES | | |
| Urban Issues Library | F 99 | On CUWRM web site |
| Salmon in the City conference proceedings | | On CUWRM web site |

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Writing for Success
February 20, 25, 27, March 4 and 6, 2002 • Seattle

Storm and Surface Water Monitoring
March 12 and 13, 2002 • Seattle

Construction Site Erosion and Pollution Control
May 15 and 16, 2002 • Seattle

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March 12–14, 2002 • Lacey
May 8–10, 2002 • Seattle

Basic Highway Capacity 2000
January 23–25, 2002 • Seattle
June 11–13, 2002 • Spokane

Construction Inspection of Public Works Projects
January 28–29, 2002 • Spokane

Public Works Construction Project Management
January 31-February 1, 2002 • Spokane

Manual on Uniform Traffic Control Devices (MUTCD)
February 6–8, 2002 • Seattle
February 11–13, 2002 • Lacey

Introduction to Retaining Wall Type Selection and Layout
March 19, 2002 • Lacey

Culvert Repair and Rehabilitation
April 9–10, 2002 • Seattle

Legal Liability for Transportation Professionals
April 16–17, 2002 • Vancouver, WA

Traffic Calming: Techniques and Management
April 29–May 1, 2002 • Spokane

Bridge Foundation Design
May 15–17, 2002 • Spokane

Fundamentals of Traffic Engineering
May 29–31, 2002 • Seattle

## EPP—ENGINEERING PROFESSIONAL PROGRAMS

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# The Washington Water RESOURCE

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# URBANIZATION AND STREAM QUALITY IMPAIRMENT[1]

Richard D. Klein[2]

ABSTRACT: A study was conducted in the Piedmont province of Maryland to determine if a relationship exists between stream quality and the extent of watershed urbanization. During the first phase of the study 27 small watersheds, having similar characteristics but varied according to land use, were investigated. Using these controlled conditions, eliminating as many interferences as possible, this first phase was intended to determine if a definite relationship did exist between the two factors. Finding that the first phase was successful the second was initiated which consisted of a comparison of biological sampling data, from other studies, with degree of watershed urbanization. The purpose of this second phase was to ascertain if the relationship between degrees of urbanization and decline in stream quality was linear as watershed area increased and in streams spread throughout the Maryland Piedmont. The principal finding of this study was that stream quality impairment is first evidenced when watershed imperviousness reaches 12%, but does not become severe until imperviousness reaches 30%.
(KEY TERMS: urbanization; impervious surfacings; benthos; fish; toxic substances; stream quality impairment; sediment; migration barriers; baseflow; storm water; temperature.)

## INTRODUCTION

The biological community structure of urban streams is generally quite different from that of streams draining rural or natural watersheds. Specifically, the typical urban stream exhibits a paucity of life with the inhabiting organisms being those normally associated with stressed environments.

The study described herein, was undertaken to determine if a direct relationship exists between the degree of stream quality impairment and the extent of watershed urbanization. If such relationships were found then it should be possible to develop a series of recommendations for the amount of urbanization that can occur without impairing stream quality.

The factors which affect urban stream quality, when point source discharges and sewerline overflows are absent, include:

Increased storm water runoff which in turn causes an increase in the frequency and severity of flooding, accelerated channel erosion, and alteration of the stream bed composition.

Reduced base flow.

Alteration of the natural stream temperature regimen.

Alteration of the character and volume of energy inputs to the stream.

Increased entry of toxic substances such as heavy metals, pesticides, oil, road salt, detergents, etc.

Elevated nutrient inputs to the stream.

For the purposes of this study, percent impervious area was selected as the characteristic common to urban watersheds to be used in relating degrees of impairment to the extent of urbanization. The study was divided into two phases:

1. The examination of several stream quality parameters in a series of small watersheds having similar characteristics but varied according to land use. The specific parameters examined in each were baseflow, the benthic community structure, and fish populations.

2. A review of literature relevant to the effects of urbanization upon stream quality and a comparison of biological sampling results, from other studies, with the degree of watershed urbanization.

It was assumed that the effects of urbanization upon stream quality would vary between physiographic provinces. Therefore the sampling data presented here are restricted to the Piedmont province.

## METHODS

The sampling program conducted during this study was designed to compare several stream quality parameters under carefully controlled conditions, eliminating as many variables as possible. This sampling effort was intended to determine if streams draining watersheds of similar size, geology, shape and geographical location, but varied according to land use, would exhibit decreasing quality as the degree of urbanization increased using percent impervious area as the unit of measure.

Percent impervious area was determined by first determining the watershed land use from the 1973 county land use maps prepared by the Earth Satellite Corporation for the Maryland Department of State Planning. Percent impervious area was then computed using the figures given in *Urban Hydrology for Small Watersheds* (SCS, 1975) and Graham, *et al.* (1974).

Twenty-three small watersheds, ranging from 2.4 $km^2$ – 7.3 $km^2$ in size, were selected to determine the degree of baseflow reduction. Two precautions were taken to reduce the possibility of error resulting from highly localized storm events -- first, the discharge of each stream was measured on three separate dates; and secondly, the measurement dates were selected to allow the passage of at least one week since the last significant rainfall.

The first of the three measurements were made with the Marsh-McBirney Model 201 electromagnetic current meter. The second and third measurements were made with a Price pygmy current meter. All measurements were made in accordance with the procedures recommended by Buchanan and Somers (1973). The results of each series of flow measurements were averaged, then divided by the planimetered drainage area of each watershed, yielding a discharge value expressed in cubic meters per second per square kilometer ($cms/km^2$).

Benthic organisms were collected with a Surber square foot sampler. At each of the streams sampled, care was taken to avoid the influence of nearby [illegible]ssings or other physical alterations of the channel. A total of three 0.09 $m^2$ botto[illegible]ples were

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collected fr single riffle at each study stream. The sampler contents were placed in a U. S. No. 30 ... e bucket and then transferred to a plastic container in which the contents were preserved in 70% ethanol. The Surber sampling was carried out in accordance with *Biological Field and Laboratory Methods* (Weber, 1973).

Due to the small size of the study streams (most less than 2 meters wide) fish collections were made with fine mesh rectangular dip nets. On each of the 11 streams sampled two collectors waded a 100-meter section, in an upstream direction, sampling every microhabitat encountered. At the end of this first section the specimens collected were examined to determine the species. Then an additional 50-meter section was sampled and at the end another species census was made. If any new species were collected then additional 50-meter sections were sampled until no new species were obtained.

## RESULTS

A definite relationship was found between baseflow and watershed imperviousness as illustrated in Figure 1. Baisman Run, the watershed of which 70 percent is woodland. consistently had the highest discharge per square kilometer of drainage area. Redhouse Run, which drains the eastern perimeter of Baltimore City and is covered by impervious materials over 38 percent of its 4.4 $km^2$ watershed, was dry on the dates investigated. Generally, as watershed imperviousness increases, baseflow diminishes.

Of the 15 benthic samples collected, the three from the control (wooded watersheds) streams had the greatest diversity. The index used to assess diversity was that developed by Shannon and Weaver and recommended by Weber (1973). The Species Diversity Index ($\bar{d}$), expresses diversity as a number ranging from 0.00 to 4.00, with high values indicating a diverse community. The $\bar{d}$ values have been verbally expressed as: 0.00 1 ?0 = poor conditions; 1.00 – 2.00 = fair conditions; 2.00 – 3.00 = good conditions: ar-1 3.00 – 4.00 = excellent conditions.

Applying the Species Diversity Index to the benthic collections leads to questionable results due to the small sample size of most urban stream samples. Weber (1973) suggests that $\bar{d}$ values for samples containing less than 100 organisms should be evaluated with caution, if at all. Results of the Surber samples are summarized in Table 1.

Of the 11 streams in which fish collections were made, Buffalo Creek, draining an agricultural watershed, had the greatest number of species present. Five of the 9 urban streams sampled were completely devoid of fish life. The largest aquatic organism inhabiting the streams draining intensely developed areas appeared to be the crayfish. *Orconectes virilis*.

Due to the sampling techniques used, fish collections can be considered valid only from a qualitative viewpoint. It is interesting to note that in 3 of the 4 urban streams where fish were collected the dominant species was the Blacknose Dace, *Rhinichthys atralatus*. Dietemann and Giraldi (1973) stated that, " . . . this fish can tolerate a wide range of environmental conditions. It can be found where no other fish can live." Therefore the dominance of the Blacknose Dace may be assumed to be another indicator of the low quality of the urban stream environment.

## DISCUSSION

The deg character of urban streams does not result from any single factor, b rather from ... interaction of a variety of detrimental effects. Although none of t ...treams investigated in this first phase received point source discharges or se...erline over...ows, they none the less exhibited increased quality impairment as watersh... ipervious-ness increased. Following is an overview of data gathered in this study and by other workers. This discussion is provided so that the reader can fully appreciate the complexity of the stress factors present in urban streams.

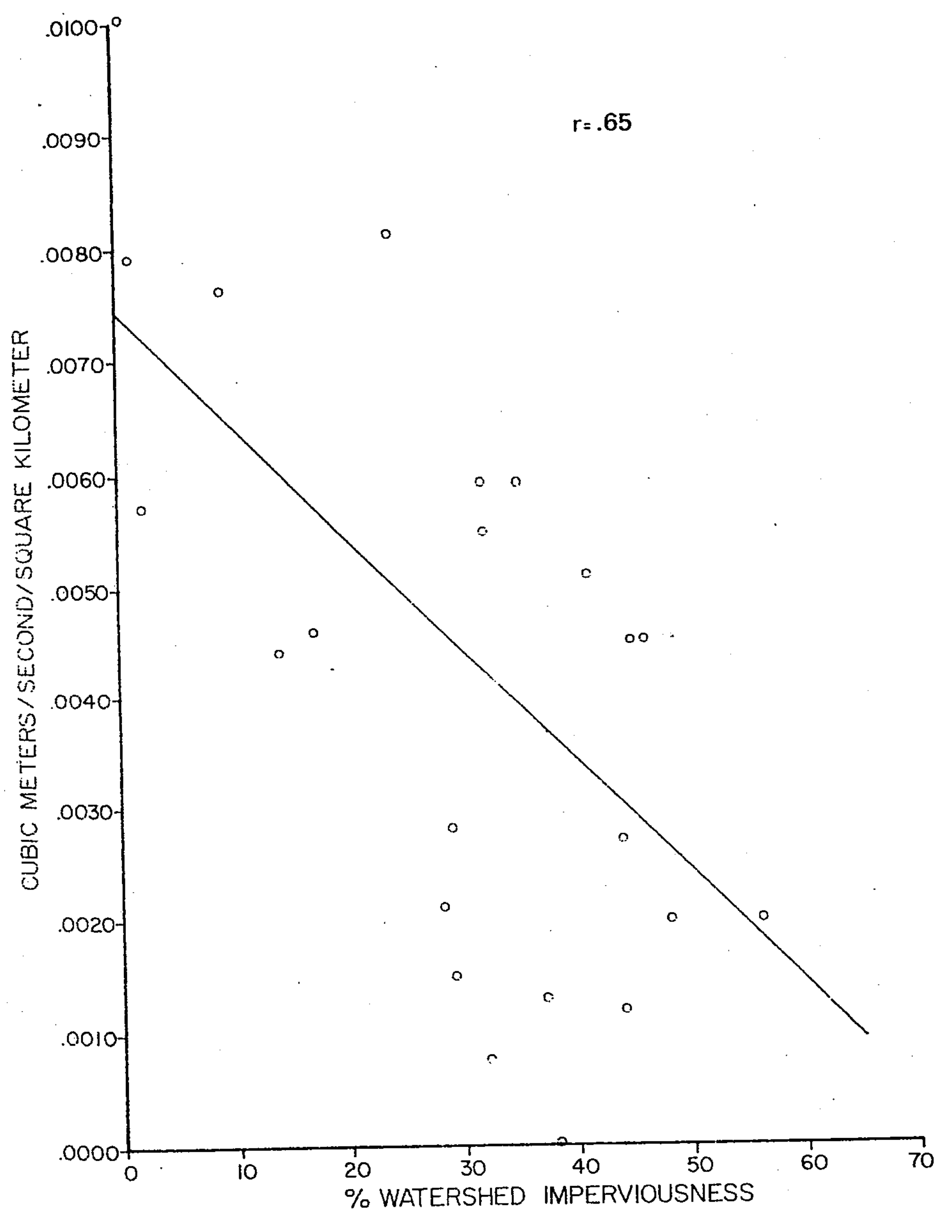


Figure 1. Base Flow Versus Watershed Imperviousness.

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TABLE 1. Results of Surber Sampling and Fish Collections Made in Baltimore County, Maryland.

| Stream | Dominant Land Use | Impervious Area | Surber Sampling Results | | | Fish Collections | | |
|---|---|---|---|---|---|---|---|---|
| | | | $\bar{d}$ | Organisms* Collected | Taxa Collected | Organisms Collected | Species Collected | Dominant Species |
| Unnamed Tributary to Gunpowder Falls | Forest | 0% | 3.33 | 181 | 19 | Not Sampled | | |
| Panther Branch | Forest | 1% | 2.85 | 89 | 16 | Not Sampled | | |
| Baisman Run | Forest | 0% | 2.48 | 122 | 12 | 19 | 2 | Rosyside Dace (*Clinostomus funduloides*) |
| Buffalo Creek | Agric. | 0% | 1.92 | 315 | 18 | 61 | 6 | Creek Chub (*Semotilus atromaculatus*) |
| Long Quarter Branch | Resid. | 44% | 1.78 | 203 | 4 | 0 | 0 | |
| Spring Branch | Resid. | 32% | 1.45 | 230 | 8 | 0 | 0 | |
| Unnamed Tributary to Beaverdam Run | Resid. | 41% | 1.45 | 97 | 6 | 0 | 0 | |
| Keysers Run | Agric. | 0% | 0.96 | 519 | 9 | Not Sampled | | |
| Slaughterhouse Branch | Resid. | 17% | 0.94 | 167 | 7 | 32 | 2 | Blacknose Dace (*Rhinichthus atralatus*) |
| Bens Run | Resid. | 23% | | 20 | 7 | 2 | 1 | Blacknose Dace (*Rhinichthus atralatus*) |
| Unnamed Tributary to Gwynns Falls | Resid. | 48% | | 6 | 4 | 3 | 1 | Creek Chub (*Semotilus atromaculatus*) |
| Perring Run | Resid. | 48% | | 18 | 4 | 0 | 0 | |
| North Branch-Whitemarsh Run | Resid. | 28% | | 8 | 2 | 0 | 0 | |
| Whitemarsh Run | Resid. | 56% | | 10 | 3 | 0 | 0 | |
| Jennifer Run | Resid. | 28% | | 12 | 2 | 54 | 2 | Blacknose Dace (*Rhinichthus atralatus*) |

*All macroinvertebrates collected were identified to genera except the Chironomids which, with the exception of one sample, were represented by only a few individuals appearing to be of the same genera.

### *Construction Phase*

The first environmental insult resulting from urbanization occurs during the construction phase when denuded earth is exposed to the full force of erosion. Wolman (1964), discussing very small watersheds stated, "Because construction denudes the natural cover and exposes the soil beneath, the tonnage of sediment derived by erosion from an acre of ground under construction in developments and highways may exceed 20,000 to 40,000 times the amount eroded from farms and woodlands in an equivalent period of time." In her study of the Patuxent River basin, Fox (1974) found urbanizing watersheds were generating 9 times as much sediment as rural or natural drainage areas. Fox also found that with a steady sediment source sand covered the natural stream bed in 2 to 3 months. Sand, when it is of the shifting, unstable variety, provides one of the poorest substrates for benthic life. Fox determined that the total volume of sand in an urbanizing stream could be 15 times that found in nearby rural watercourses. Her estimates indicated that 10 to 50 years were required for a stream to recover from the construction phase of urbanization and in some cases hundreds of years might be needed for full recovery. Fox also concluded that an average of 4.8 to 5.6 kilometers of stream below a sediment source were affected by the eroded soil particles.

### *Runoff Quantity*

When the construction phase is completed and the soil stabilized the land surface is left in an altered hydrologic condition, the net effect of which is increased storm water runoff and decreased infiltration. Leopold (1968), stated that a direct relationship exists between the number of bankfull flows that occur annually and the extent of urbanization. When the watershed is in a rural or natural condition bankfull flows usually recur once annually. When watershed imperviousness reaches 40 percent bankfull flows occur 3 times yearly. When the drainage area is completely developed the stream fills from bed to banktop with runoff an average of 5.6 times each year. Hoopes (1975), in his study of the effects of Hurricane Agnes on a central Pennsylvania stream, found that the flood had reduced the young-of-the-year trout population by 96 percent. In another study Elwood and Waters (1969) found that two-year classes of Brook Trout, *Salmo fontinalis* Mitchill, were nearly eliminated by 4 severe floods which occurred over a two-year period. They also found that invertebrate populations were severely damaged by the floods. Under natural conditions such catastrophic events are usually spread out over a long period of time and therefore have a minimal effect upon the overall health of the stream. Some workers have even stated that such floods are essential to stream health through their scouring and cleansing effect. But as floods become more frequent the resiliency of the stream community is strained, making it difficult to rebuild stable populations. As Leopold pointed out the volume of storm water runoff and subsequent flooding increases as urbanization intensifies. For instance, estimates made by the author using the Peak Discharge Method (WRA. 1975) indicates that a stream, typical of that found in the Maryland Piedmont, with a watershed of 2.6 square kilometers in area, would carry 4.25 cms at the flood peak during a 100-year storm when the watershed is completely forest covered. This same stream would be subjected to a flood peak of equal volume (4.25 cms) once every 5 years when watershed imperviousness reaches 25%. At a watershed imperviousness degree of 38 percent this same peak volume would recur once every 2.5 years. And when 65 percent of the watershed is covered by impervious surfacings the former 100-year peak discharge of 4.25 cms would recur or ...ually.

**Channel M[illegible]logy.** The increased runoff delivered to urban streams causes several changes in ch[illegible] morphology. Robinson (1976), in his study of 8 small watersheds located in the Piedmont province of Maryland, found that streams draining developed watersheds averaged twice the channel width of rural streams. Hammer (1972), reporting on 78 small watersheds near Philadelphia found much the same effect upon urban stream morphology although some of the streams he investigated had channel widths 3.8 times that of nearby rural streams. Fox (1964), in her study of 64 points in the Patuxent River basin, found much the same degree of channel widening in urban streams. Channel enlargement, resulting primarily from erosion of the banks, introduces a rather high quantity of sediment into the stream. Robinson (1976) estimated that the total quantity of sediment resulting from erosion occurring during the enlargement period averages 2,300 $m^3/km^2$ of drainage area. Robinson also estimated that some 15 years are required for the enlargement process to end. He also found that the substrate of urban streams tends to be composed of coarser particles, with a paucity of the sand and silt fractions, than that found in rural watercourses. The ever-changing character of urban streams during the enlargement process, coupled with the sediment inputs, would in itself make it difficult for aquatic life to build stable populations much less those resembling preurbanization communities. Once the enlargement process ends, aquatic life may still be faced with high velocity floodwaters and the coarser bed materials. These larger bed particles could increase the potential for washout or predation for those organisms which lay their eggs or dwell within the stream bed.

**Migration Barriers.** Many of the Piedmont streams flowing to tidewater support spawning migrations of anadromous fish species, particularly in their lower reaches (O'Dell, *et al.*, 1975). Debris dams – accumulations of logs, brush, litter, etc. – are one of several obstacles limiting the extent of a stream available to the spawning fish. Fox (1974) found that in the Patuxent River system debris dams occur at an average of once every 335 meters in streams draining natural watersheds, while urban streams average a debris dam every 73 meters. Therefore, migrating fishes would either find upstream movement more difficult or halted at a closer distance to the mouth in urban as compared to natural streams. This problem would not solely affect anadromous species since most stream dwelling fishes also make annual migrations.

**Baseflow.** Tennant (1975) found that the suitability of a stream for fish declines as baseflows diminish. The adverse affects attributed to reduced flow include loss of cover, reduced velocities, alteration of the temperature regimen, and impairment of the ease with which riffles could be negotiated. Tennant states that severe degradation of the suitability of a stream for fish occurs when the baseflow drops to 10 percent or less of the average discharge. Analysis of the U.S. Geological Survey data on 14 gauged streams, by this writer, in Baltimore and Carroll Counties, Maryland, indicates that discharges in this region average 0.092 $cms/km^2$. The author found that baseflow is reduced to 10 percent of the regional average when 65 percent of the watershed is covered by impervious materials (see Figure 1). Tennant also stated that "fair to degrading" conditions are maintained when April to September baseflows drop to 30 percent of the average. The author also determined that flows reach this level when 45 percent of the watershed is covered by impervious materials. It is important to remember that the discharge measurements made in this study were not taken at the time of year, autumn, when streams [illegible]ually reach their annual low flow point. Therefore, the 10 percent [illegible] 0 percent flow values may occur in watersheds with lesser degrees of urbanization than given above.

Leopold (1968) states that, "Reduced volume also effects low flows because in any series of storms the larger the percentage of direct runoff, the smaller the amount of water available for soil moisture replenishment and for ground-water storage. An increase in total runoff from a given series of storms as a result of imperviousness results in decreased ground-water recharge and decreased low flows. Thus increased imperviousness has the effect of increasing flood peaks during storm periods and decreasing low flows between storms." Hammer (1973) also concluded that increased imperviousness reduces infiltration and therefore baseflows. In his study of Philadelphia streams Hammer found a steady decline in baseflow per square kilometer of drainage area until watershed imperviousness reached 40 percent to 50 percent. In these intensely developed watersheds he theorized that municipal water imported to the drainage area was offsetting, somewhat, the effects of reduced infiltration. Hollis (1976) in summarizing the results of other studies found that decreased baseflow, as a result of urbanization, is less likely to occur than baseflow increases. It appears that the direction baseflow changes take is dependent upon the particular physiographic province a stream is located within. In the coastal plain of Maryland, where bank soil tends to be relatively permeable, it is possible that increased flooding, resulting from urbanization, could also increase the volume of water stored in bank soils then released during post-flood periods and therefore baseflow might increase. But in the Piedmont, with its silty soils, perhaps bank storage is insufficient to offset the effects of reduced upland infiltration in urbanized watersheds. Additionally, one other possible explanation exists for the relationship between urbanization and baseflow documented in this study. As stated earlier Robinson (1976) found that urban stream beds tend to consist of coarser particles. It is possible that a portion of the flow may be traveling beneath the bed surface through the coarser particles. Whatever the reason, it appears certain that baseflow does diminish as imperviousness increases in the Maryland Piedmont.



**Temperature.** Several of the changes wrought by urbanization can affect the natural stream temperature regimen. The effect of reduced shade upon maximum stream temperatures has been well documented (Brown, 1969; Brown and Krygier, 1970; O'Dell, 1971; Ringler and Hall, 1975; and Hartley, 1975). The author (Klein, 1977) documented an 11°C difference between a wooded section along a Harford County, Maryland, stream and a poorly shaded pasture section of the same stream located 1.2 km below the woodland measurement point. Reductions in the amount of shading afforded urban streams results from bank alterations during sewerline installations, channel realignment projects and other construction activities. The two-to-four-fold widening of the channel due to increased runoff and enlargement not only reduces the amount of the stream shaded, but also results in shallower water depths which further adds to the degree of heat loss and gain. Under conditions of reduced shade diurnal temperature fluctuations are also greater. During July 1977 I found that the differences between daily minimum and maximum temperatures along a Harford County, Maryland, stream were 1.9°C in a wooded section, 4.3°C in a shrub lined section, and 8.3°C in a pasture reach. Pluhowski (1970) found when investigating 5 streams on Long Island, New York, that urban streams reach lower winter temperatures, 1.5° - 3°C, than relatively undisturbed streams.

The temperature of headwater streams is influenced greatly by gro[illegible] water inflow. Data collected on Jones Falls in Baltimore County, Maryland, deter[illegible] that ground water, as it surfaces, has a temperature of $10^{o} - 11^{o}C$ (J. A. Gracie, 1977 personal communication). As a result the temperature of streams near the sources of ground water inflow, such as upper Jones Falls, rarely falls below $7.8^{o}C$ in the winter and infrequently rises above $20^{o}C$ in the summer. Therefore, reducing ground water inflow can further the degree of departure from the natural stream temperature regimen, allowing streams which were normally ice free through winter to freeze or to reach critically high summer temperatures.

*Runoff Quality*

The quality of urban runoff has been likened to that of raw sewage and in several respects can be 2 to 10 times as polluted. Though the quantity of specific pollutants contributed by urban runoff is high it is important to remember that the dilution rate is equally large, yet the net effect of the contaminants exported from urban areas remains uncertain due to a paucity of basic data. For instance, though urban runoff contributes a large volume of oxygen demanding material it seems relatively rare for the oxygen content of urban streams to be depleted appreciably. Davis and Hammer (1976) attributed this to the short residence time of the material in the stream.

**Nutrients.** Nutrient loadings are also quite high from urbanized watersheds. Omernik (1977), in his graphical description of loading rates from various land uses, illustrated that mean total nitrogen exports from urban areas was second only to intensively farmed watersheds. Mean total phosphorus exports were second only to cleared, unproductive land. While the effect of high nutrient loads upon streams seems unclear, Cole (1973) found that macroinvertebrate diversity declined from a high of 3.51 above a nutrient input source to 1.31 downstream of the source. The principal effect of nutrients upon a stream would be the stimulation of algae and other aquatic plant growth. When plant growth becomes intense night time dissolved oxygen levels can become critically low. Also the community structure could be altered in favor of those organisms capable of exploiting the increased plant growth. Under natural conditions algae growth constitutes a mere 1 percent of the energy budget of headwater streams (Cummins, 1974) where shading bank vegetation appears to be the primary factor holding plant growth in check. When the watershed is urbanized a portion of the shading vegetation is usually removed. With the combination of increased sunlight and nutrient inputs, conditions would seem right for a considerable increase in algae populations. It appears, however, that such algae blooms seldom occur in urban streams. The author has rarely witnessed intense or even moderate algae growth in streams draining highly developed watersheds. Perhaps these aquatic plants are just as susceptible to the adverse effects of urbanization as are other stream dwelling organisms.

**Toxic Substances.** Heavy metal inputs from urban areas can be high also. Laxen and Harrison (1977) reported that lead concentrations in highway runoff were $10^3$ to $10^4$ times that of background levels. The Northern Virginia Planning District Commission (1977), in its interim report on the Occoquan/Four Mile Run Nonpoint Source Correlation Study, does provide a comparison between lead and zinc loadings from various land uses. As illustrated in Figure 2, the loading rates of these two metals rises as watershed imperviousness increases. In a Massachusetts study Berger (1976) found that, "... urban runoff appear[illegible] exert a significant negative impact on the benthic biota. Analysis of sediment, de[illegible] and benthic macroinvertebrates revealed unexpectedly high an[illegible] normally acute toxic concentrations of several metals." Yet Berger concluded with the caution that the specific source of these metals remains to be determined.

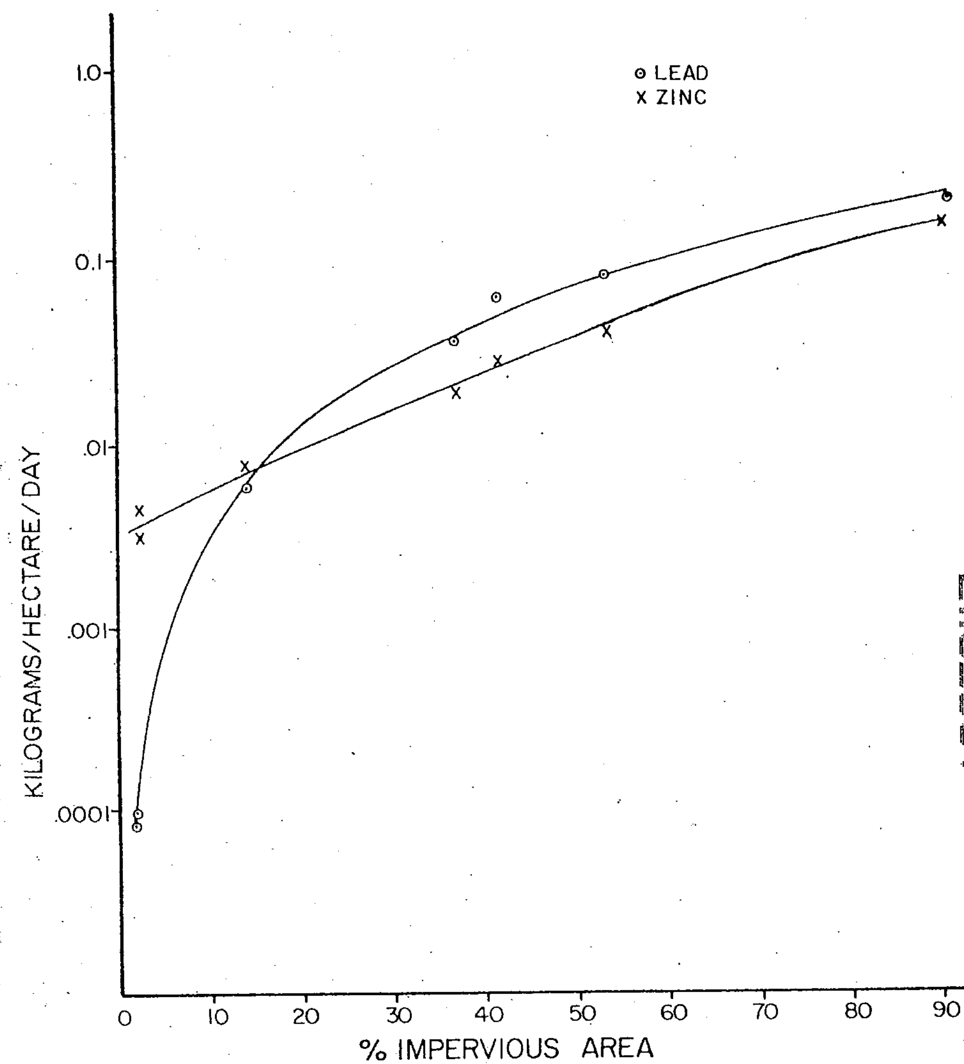


Figure 2. Total Extractable Metals Loadings Versus Watershed Imperviousness.

Bryan (1972), in summarizing pesticide loadings found in his study and that of others, stated that rural runoff contained a mean value of 0.43 ug/l while the mean of urban runoff ranged from 1.16 to 1.70 ug/l.

In 1973 70 million liters of automotive lubricants were sold in Maryland. Of this quantity the final disposition of only 45 million liters could be accounted for with the whereabouts of the remainder uncertain. A 1973 estimate indicated th[illegible]-it-yourself" mechanics drain 19 million liters of used oil from Maryland cars annu[illegible] [illegible]oor-to-door survey (Kle 76) conducted by the Baltimore County Save Our Streams program indicated that 9 percent of the do-it-yourselfers dispose of used oil by pouring it into strom drains or gutters. In the early 1970's it was estimated that 9.5 million liters of oil entered Baltimore Harbor annually and originated from runoff and small diffuse sources. Whipple, *et al.* (1975), estimated that runoff from Philadelphia carried 3,600 kilograms of oil on an average daily basis. Therefore, it appears certain that a considerable quantity of oil does reach urban streams, adding its share to the impairment of these waters.

McKee and Wolf (1963) reported that chloride concentrations of 400 mg/l were harmful to trout with other species tolerating levels up to 9,000 mg/l. In urban watersheds where sewerlines are present, and not overflowing, street salting appears to be the principal source of chloride entry into streams. Hawkins and Judd (1972) reported that road salt washoff resulted in a chloride concentration of 11,000 mg/l in a small New York state stream. A Chicago study (APWA, 1969) documented chloride concentrations in receiving waters draining a salt treated highway of 25,100 mg/l. Critikos and Klein (1978), while collecting daily samples from a small urban stream, found that chloride concentrations over a 23-day period averaged 219 mg/l and ranged from 113 to 410 mg/l. The tolerance levels given above are based upon test periods ranging up to 96 hours. It is possible that exposure to concentrations of chloride of 200 mg/l over a 23-day period could well be at or above the long-term tolerance level of sensitive organisms.

*Summary*

As indicated earlier the degraded character of urban streams is not the result of any single detrimental factor, but the synergistic interaction of all the detrimental factors discussed above. Analysis of the baseflow data from the present study indicates that "severe degradation" as defined by Tennant, occurs when 30 percent to 70 percent of the watershed is covered by impervious surfacings. All the urban streams whose watersheds fell within this range of imperviousness evidenced severely degraded conditions for aquatic life in the form of either reduced benthic communities or the absence of fish life.

When watershed imperviousness ranged from 30 percent to 45 percent baseflows were reduced to Tennant's "fair to degrading" level. Slaughterhouse Branch, which was the only urban stream supporting both an abundant benthic community and a fish population, was biologically in the best condition of any of the urban watercourses investigated. It is interesting to note that its benthic Species Diversity Index, verbally expressed, is on the borderline between "poor to fair," agreeing with the verbal description of its baseflow.

To determine if the relationship between degree of urbanization and stream quality remains constant as watershed size increases and throughout the Piedmont province, 78 fish collections from Montgomery and Prince Georges County streams were examined (Dietemann, 1975; Dietemann and Giraldi, 1973). The Species Diversity Index ($\bar{d}$) was calculated for each collection then plotted against watershed percent imperviousness using the same procedures outlined earlier, the results of which are illustrated in Figure 3. Though a fair amount of scatter can be seen in the graph, a generally direct relationship does exist between the degree of urbanization and the diversity of fish populations.

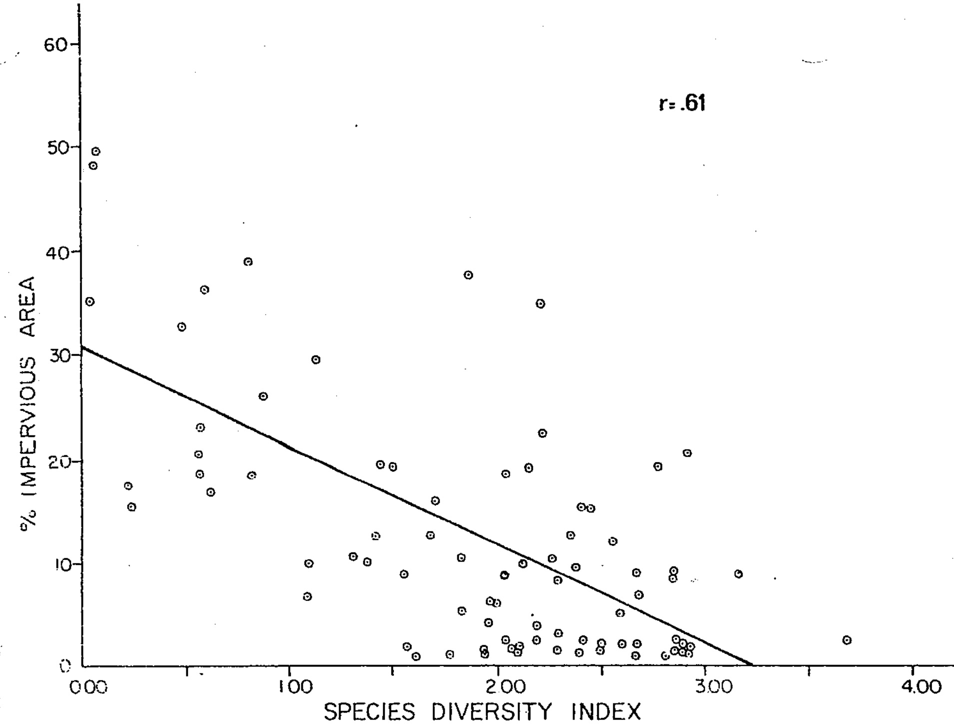


Figure 3. Montgomery/Prince Georges County Fish Collections Versus Watershed Imperviousness.

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## CONCLUSIONS

It is the author's opinion that impairment begins when stream quality drops from good to fair. Using these guidelines, data from the first phase of the study indicates that stream quality impairment is initially evidenced when watershed imperviousness reaches 15 percent. From Figure 3, which is based on fish collections made in streams draining watersheds 5 to 130 km$^2$, note that the line of regression crosses the Species Diversity Index of 2.00, which separates the good to fair range at the 12 percent imperviousness point. From these data two recommendations can be made:

1. Generally, stream quality impairment can be prevented if watershed imperviousness does not exceed 15 percent.

2. For the more sensitive stream ecosystems, such as those supporting self-sustaining trout populations, watershed imperviousness should not exceed 10 percent.

If a jurisdiction were to decide to limit urbanization in undeveloped areas to the recommendations given above, the degree of development allowed should not exceed that given in Table 2. Should a jurisdiction decide to adopt these recommendations it should consider duplicating the study described herein once every 5 to 10 years, or whenever a new control strategy is applied to the detriments resulting from urbanization. This precaution would prevent a landowner/developer from being penalized by an outdated restriction and would also serve as a stimulus for designing developments to be as environmentally compatible as practical.

TABLE 2. Allowable Watershed Development Rates Based Upon This Study.

| Land Use Category | Imperviousness | Maximum Amount of Watershed that can be Developed Based Upon an Imperviousness of 10% | 15% |
|---|---|---|---|
| Individual Homes | | | |
| 0.40 Hectare (1.00 acre) Lot | 20% | 50% | 75% |
| 0.20 Hectare (0.50 acre) Lot | 25% | 40% | 60% |
| 0.13 Hectare (0.33 acre) Lot | 30% | 33% | 50% |
| 0.10 Hectare (0.25 acre) Lot | 38% | 26% | 29% |
| 0.05 Hectare (0.12 acre) Lot | 65% | 15% | 23% |
| Townhouse/Garden Apartments | 44% | 22% | 33% |
| High-Rise Residential | 56% | 18% | 27% |
| Industrial Districts | 75% | 13% | 20% |
| Commercial/Business Area | 85% | 12% | 18% |
| Shopping Centers | 95% | 11% | 16% |

Some controls are currently being applied or planned to reduce the effects or urbanization upon stream quality. In the Maryland jurisdictions located in the Piedmont, where storm water management is required for most new developments, Detention/Retention structures dominate. These devices, consisting mostly of open ponds or underground storage areas, are intended to temporarily detain a portion of the runoff. As a result the "peak discharge" volume is lessened along with downstream erosion and scouring. While this approach does reduce some of the physical effects of urbanization it has a minimal impact upon the runoff quality. Currently, infiltration systems make up only a small portion of the control strategies outlined in Storm Water Management Plans. This fact is said to be due to the difficulty involved in designing these systems. Yet if infiltration systems were to dominate, not only would erosion and scouring be reduced, but baseflows would also be improved through the added recharge of the ground water system. Additionally, percolation through the soil would provide removal of the quality constituents of urban runoff. But this raises another question. Neither the filtration, adsorption, nor ion exchange capacity of a soil is infinite. In 50 years after their installation would we find that a healthier stream has been purchased at a price of a contaminated aquifer? And once the neutralization capacity of the soil is exhausted would the pollutants eventually reach the stream anyway? Unfortunately once an infiltration system failed it would not be as easy to correct as a failing septic system, in which case a new system is simply installed. Infiltration systems designed as storm water management devices require a rather extensive amount of land to handle the volume of runoff delivered to the device. [illegible] f money were available to install the device, how frequently would sufficient land f[illegible] new structure be available in an existing development?

The third option available for controlling urban runoff is treatment. This option is a rather expensive one with the cost of providing secondary treatment for all of Maryland's urban runoff placed at $6 billion. If only primary treatment were used, the cost would run about $500 million.

In summary, four options are available to reduce the adverse affects or urbanization upon stream quality. Detention/Retention systems will reduce the velocity-scour problem resulting from urbanization with minimal impact on the other detrimental effects. Infiltration systems offer a means of temporarily lowering the impact of land development but improved stream quality may be exchanged for a polluted aquifer. Treatment of storm water would also mitigate many of the adverse affects of urbanization and provide a more lasting improvement than infiltration systems alone. Yet treatment appears justifiable, due to its high cost, in only the severest of situations.

The last alternative is that proposed by this study. Limiting watershed development to the rates recommended in Table 2 would preserve stream quality with the only costs involved being that incurred by the landowner due to building restrictions. It is not unlikely that the long-term reliability of existing control strategies such as infiltration systems will be found acceptable. Nor is it unlikely that new control strategies will be developed to resolve the adverse affects of urbanization upon stream quality. Therefore, the landowner/developer will probably be faced with only a temporary restriction upon the use of his property should this fourth approach be adopted by a jurisdiction.


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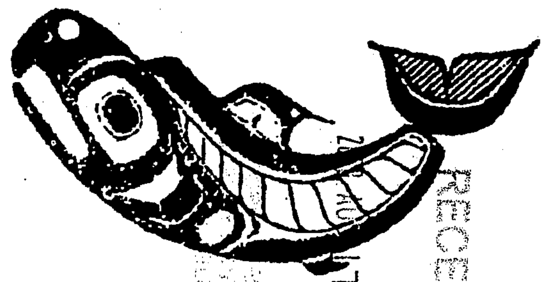
Sent by Derek Booth

*Low levels of watershed development found to impair stream quality*

# Effects Of Urbanization On Small Streams In The Puget Sound Lowland Ecoregion





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**University of Washington, Seattle, Washington**

The Pacific Northwest, like many areas of North America, is experiencing an increase in urban development that is rapidly expanding into remaining natural aquatic ecosystems. In the Puget Sound lowland (PSL) ecoregion, the natural resources most directly affected by watershed development are small streams and associated wetlands. Stream ecosystems are critical spawning and rearing habitat for several species of native salmonids including coho and cutthroat trout and many salmon species. These fish, especially the salmon, hold great ecological, cultural, and socioeconomic value to the peoples of the region. Despite this value, the wild salmonid resource is in considerable jeopardy of being lost to future generations. Over the past century, salmon have disappeared from about 40% of their historical range and many of the remaining populations (especially in urbanizing areas) are severely depressed (Nehlsen et al. 1991). There is no one reason for this decline. The cumulative effects of land-use practices including timber-harvest, agriculture, and urbanization have all contributed significantly to this widely publicized "salmon crisis."

The effects of watershed urbanization on streams are well-documented (Leopold 1968; Hammer 1972; Hollis 1975; Klein 1979; Arnold et al. 1982; Booth 1991) and include extensive changes in basin hydrologic regime, channel morphologic features, and physiochemical water quality. The cumulative effect of these alterations have produced an instream habitat structure that is significantly different from that in which salmonids and associated fauna have evolved. In addition, development pressure has a negative impact on riparian forests and wetlands that are essential to natural stream function. Considerable evidence about these impacts exists from studies of urban streams in the Pacific Northwest, although most previous work has fallen short of establishing cause-effect relationships among physical and chemical impacts of urbanization and the response of aquatic biota.

> Urbanization has produced an instream habitat structure much different from that in which salmonoids have evolved.

The most obvious manifestation of urban development is an increase in impervious cover and the corresponding loss of natural vegetation. Land clearing, soil compaction, riparian corridor encroachment, and modifications to the surface water drainage network all typically accompany urbanization. Watershed urbanization is most often quantified in terms of the proportion of basin area covered by impervious surfaces (Schueler 1994; Arnold and Gibbons 1996). Although impervious surfaces themselves do not generate pollution, they are the major contributor to changes in watershed hydrology that drive many of the physical changes affecting urban streams. Basin imperviousness and runoff are directly related (Schueler 1994). In previous studies, measures of total impervious area (%TIA) of about 10% have been identified as the level at which stream ecosystem impairment begins (Klein 1979; Steedman 1988; Schueler 1994; Booth and Reinelt 1993). Recent studies suggest that this potential threshold may apply to wetlands as well.

**Glossary of Article Acronyms**

| | | |
|---|---|---|
| PSL | = | Puget Sound Lowland |
| TIA | = | Total Impervious Area |
| LWD | = | Large Woody Debris |
| IGDO | = | Intragravel Dissolved Oxygen |
| DO | = | Dissolved Oxygen |
| Km | = | Kilometer |
| m | = | Meter |

### Stream Study Design

A key objective of the Puget Sound lowland stream study conducted between 1994-1996 was to identify the linkages between landscape-level conditions and instream environmental factors, including defining the functional relationships between watershed modifications and aquatic biota. The goal was to provide a set of stream quality indices for local resource managers to use in managing urban streams and to minimize resource degradation resulting from development pressures. For example one study objective was determining the conditions for maintaining a given population or community of organisms, (such as native salmonids) at a specified level. This requires sustaining a certain set of habitat characteristics, which in turn depend on an established group of watershed conditions. A part of this overall objective was to identify any thresholds of watershed urbanization as related to instream salmonid habitat and aquatic biota. The study was designed to establish the linkages between landscape-level conditions, instream habitat characteristics, and biotic integrity. A conceptual model of this design is illustrated below:

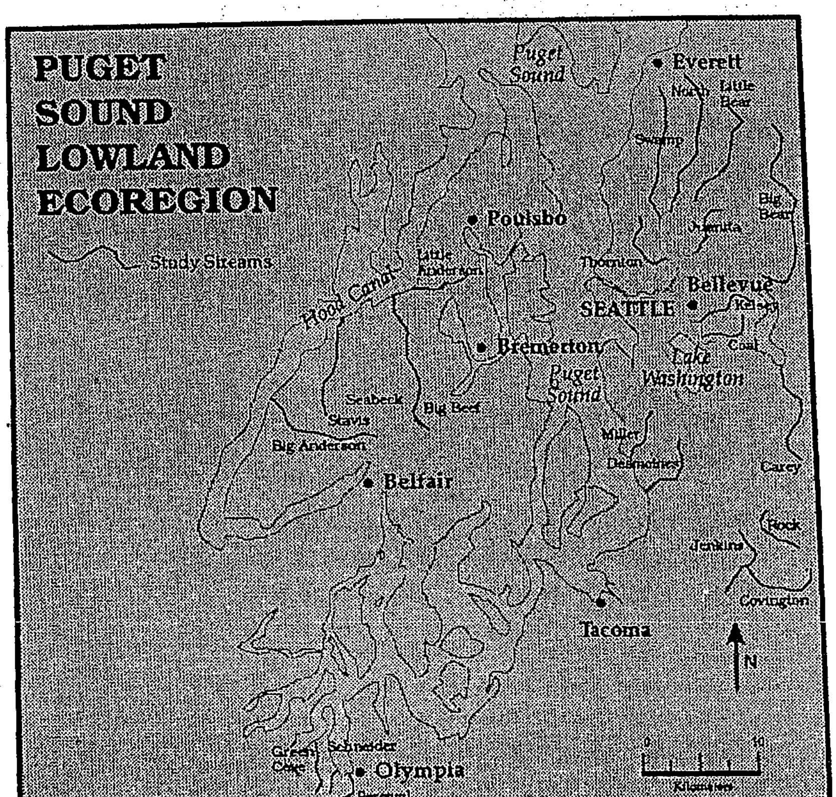
**Watershed and Riparian Characteristics => Instream Habitat Conditions => Aquatic Biota**

A subset of twenty-two small-stream watersheds was chosen to represent a range of development levels from relatively undeveloped (reference) to highly urbanized. Researchers controlled for physiographic variability by studying only streams in the Puget Sound lowland ecoregion (see Figure 1 for stream locations). Total impervious surface area (%TIA), because of its integrative nature, was used as the primary measure of watershed urbanization. The attributes of the stream catchments were established using standard watershed analysis methods including geographic information system (GIS) data, aerial photographs, basin plans, and field surveys. Impervious surface coverage, riparian integrity, instream physical habitat characteristics, chemical water quality constituents, and aquatic biota were analyzed on both watershed and stream segment scales. Discharge was continuously monitored by local agencies on ten of the study streams. Chemical water-quality monitoring (baseflow and storm events) was conducted at 23 sites on 19 of the study streams. Biological sampling (macroinvertebrates) was performed in 31 reaches on 21 of the study streams. Extensive surveys of instream physical habitat and riparian zone characteristics were made on 120 stream-segments on all 22 PSL streams, each representing local physiographic, morphologic, and sub-basin land use conditions from the headwaters to the mouth of each stream. Salmonid abundance data were obtained from public, private, and tribal sources.

All streams were third-order or smaller, ranging in basin area from 3 to 90 $km^2$, with headwater elevations less than 150 meters. Stream gradients were less than 3.5% (most were < 2%). The study watersheds represented the two general types of geologic and soil conditions found in the Puget Sound region. The underlying geology and soil types are mainly a result of the last glacial period (15,000 years ago). All but three of the watersheds were dominated by poorly drained glacial till soils, with the remaining basins dominated by glacial outwash soil types (moderately well drained).

In the undisturbed, natural forested condition, PSL catchments are capable of providing adequate natural precipitation storage in the surficial "forest-duff" layer with little runoff resulting. Development typically strips away this absorbent forest soil layer and compacts the underlying soil and exposes the underlying till layer. The typical suburban development in the Pacific Northwest has been estimated to have roughly 90% less storage capacity than under naturally forested conditions (Wigmosta et al. 1994). The latest (1990) stormwater mitigation and best management practices (BMPs) have the potential to recover only about 25% of the original storage capacity (Barker et al. 1991). Because these standards affected very little new development that occurred between 1990 and the start of this study in 1994, the basin conditions observed largely reflected the pre-1990 situation with little effective stormwater control present. Therefore, no significant conclusions could be drawn about the effectiveness of current stormwater controls (BMPs) and regulations during this research.

**Figure 1: Puget Sound Lowland (PSL) Ecoregion**



## Results and Discussion

*Watershed Conditions*

Watershed imperviousness ranged from undeveloped (%TIA<5%) to highly urbanized (%TIA>45%). Imperviousness (%TIA) was the primary measure of watershed development; however, other measures of urbanization were investigated. Calculating impervious surface area can be costly, especially if computerized methods like GIS are utilized. In addition, the land use data required for calculation of %TIA may be unavailable or inaccurate. As part of this study, a low-cost alternative to imperviousness was also investigated. Analysis demonstrated that the relationships to be discussed were very similar if development is alternatively expressed as road-density (Figure 2). This is especially relevant in that the transportation component of imperviousness often exceeds the "rooftop" component in many land-use categories (Schueler 1994). A recent study in the Puget Sound region has shown that the transportation component typically accounts for over 60% of basin imperviousness in suburban areas (City of Olympia 1994).

Watershed urbanization results in significant changes in basin hydrologic regime (Leopold 1968; Hollis 1975; Booth 1991). This was confirmed for streams in the PSL study. The ratio of modeled 2-year stormflow to mean winter baseflow (Cooper 1996), was used as an indicator of development-induced hydrologic fluctuation (Figure 3). This discharge ratio is proportional to the relative stream power, and thus is representative of the hydrologic stress on instream habitats and biota exerted by stormflow relative to baseflow conditions. The modified basin hydrologic regime was found to be one of the most influential changes resulting from watershed urbanization in the PSL region.

In addition to an increase in basin imperviousness and the resulting stormwater runoff, urbanization also affects watershed drainage-density (km of stream per $km^2$ of basin area). This was first investigated by Graf (1977). Natural, pre-development drainage-density (DD) was calculated using historic topographic maps. This was compared to the current, urbanized DD which included both the loss of natural stream channels (mostly first-order and ephemeral channels lost to grading or construction) and the increase in artificial "channels" due to road-crossings and stormwater outfalls. Not surprisingly as imperviousness increases above the 8-10% level in study watersheds so does the number of road crossings and stormwater outfalls per kilometer at a steady rate. The ratio of urban to natural drainage density was used as an indicator of urban impact.

**Figure 2: Relationship between Urbanization (%TIA) and Sub-Basin Road-Density in PSL Streams**

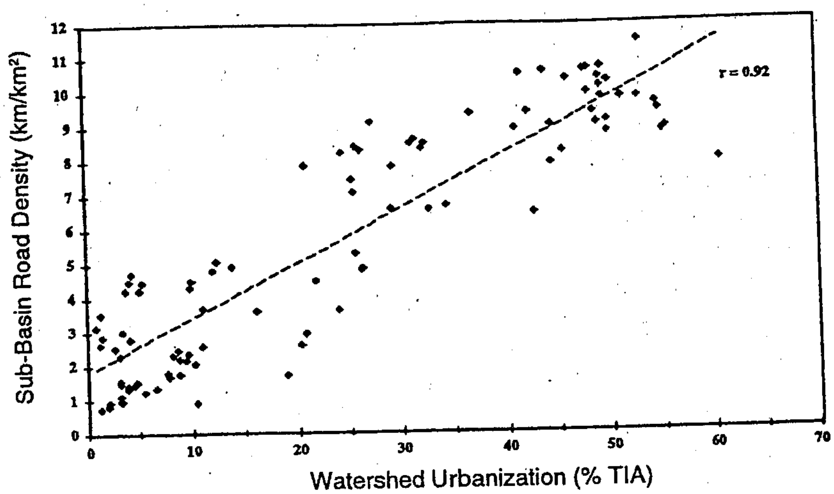
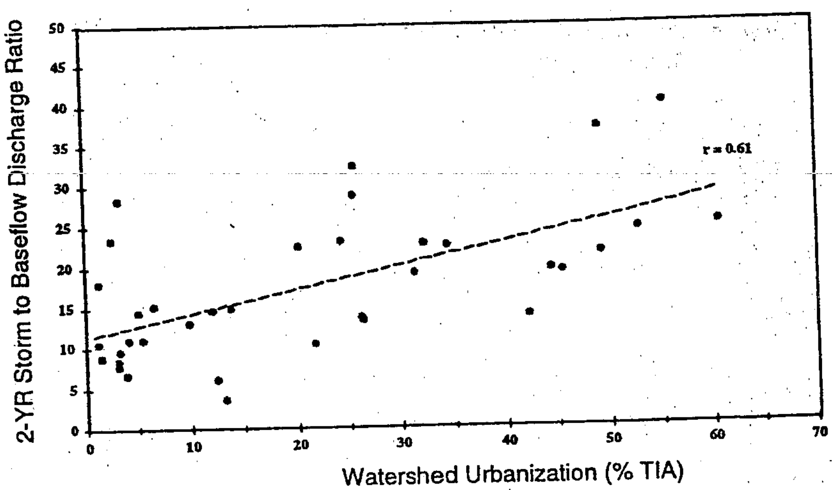



**Figure 3: Change in Basin Hydrologic Regime with Urbanization in PSL Streams**




*Riparian Conditions*

The natural riparian corridors along Pacific Northwest streams are among the most diverse, dynamic, and complex ecosystems in the region. Natural riparian integrity is characterized by wide buffers, a near-continuous corridor, and mature, coniferous forest as the dominant vegetation. The riparian corridor is frequently disturbed by flooding events, creating a naturally complex landscape.

Not surprisingly, riparian conditions were also strongly influenced by the level of development in the surrounding landscape. The impact of development activities on riparian corridors can vary widely. Very recently, regional development regulations did not specifically address riparian buffer requirements.

Sensitive area ordinances, now in effect in most local municipalities, typically require riparian buffers of 30-50 meters (100-150 feet) in width. These recently adopted regulations had little influence on the urbanized streams in the PSL study. In general, wide riparian buffers were found only in undeveloped or rural stream watersheds (Figure 4). The actual size of riparian buffer needed to protect the ecological integrity of the stream system is difficult to establish (Schueler 1995). In most cases, minimum buffer width "required" depends on the resource or beneficial use of interest and the quality of the existing riparian vegetation (Castelle et al. 1994).

The width of the riparian zone declined as watershed impervious cover increased.

Encroachment into the riparian buffer zone is pervasive, continuous, and extremely difficult to control. At the same time, riparian forests and wetlands, if maintained, appear to have a significant capacity to mitigate some of the adverse effects of development. A buffer width of less than 10 meters is generally considered functionally ineffective (Castelle et al. 1994). The fraction of riparian buffer less than 10 meters in width was used as a measure of riparian zone encroachment. In general, only streams in natural, undeveloped basins (%TIA < 10%) had less than 10% of their buffer in a nonfunctional condition. As watershed urbanization (%TIA) increased, riparian buffer encroachment also increased proportionally. The most highly urbanized streams (%TIA > 40%) in this study, generally had a large portion (upwards of 40%) of their buffers in a nonfunctional condition.

**Figure 4: Relationship Between Riparian Buffer Width and Basin Urbanization (%TIA) in PSL Streams**

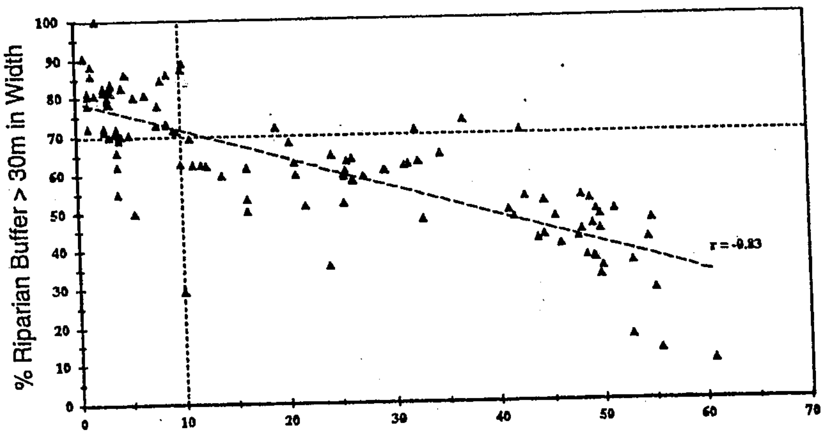
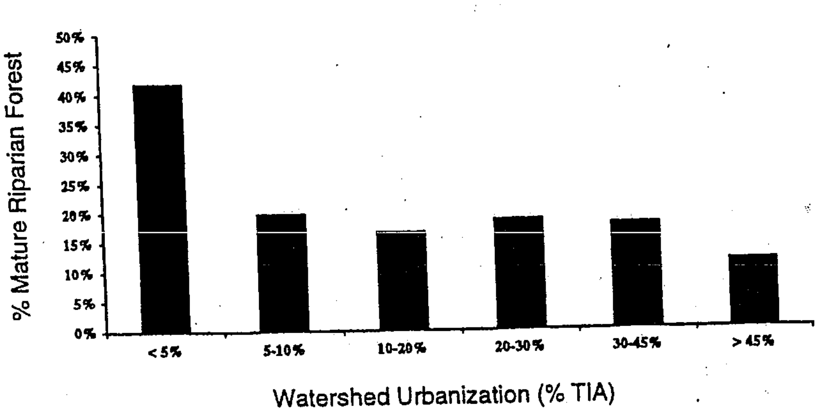



**Figure 5: Relationship Between Watershed Urbanization (%TIA) and Riparian Quality (Maturity) in PSL Streams**




The longitudinal continuity or connectivity of the riparian corridor is at least as important as the lateral riparian buffer width. A near-continuous riparian zone is the typical natural condition in the Pacific Northwest (Naiman 1992). Fragmentation of the riparian corridor in urban watersheds can come from a variety of human impacts; the most common and potentially damaging being road crossings. In the PSL stream study, the number of stream crossings (roads, trails, and utilities) increased in proportion to basin development intensity. All but one undeveloped stream (%TIA < 10%) had, on average, less than one riparian break per km of stream. Of the highly urbanized streams (%TIA > 40%), all but one had greater than two breaks per kilometer. Based on current development patterns in the PSL, only rural land use consistently maintained breaks in the riparian corridor to < 2 per kilometer of stream length. In general, the more fragmented and asymmetrical the buffer, the wider it needs to be to perform the desired functions (Barton et al. 1985).

The riparian zone was also examined on a qualitative basis. Mature forest, young forest, and riparian wetlands were considered "natural" as opposed to residential or commercial development. From an ecological perspective, mature forest or riparian wetlands are the two most ecologically functional riparian conditions in the Pacific Northwest (Gregory et al. 1991). In the 22 PSL streams, riparian maturity was also found to be strongly influenced by watershed development. Only the natural streams (%TIA < 5%) had a substantial portion of their riparian corridor as mature forest (40% or greater), while urban streams consistently had little mature riparian area (Figure 5). In addition, none of the urbanized PSL streams retained more than 25% of their natural floodplain area.

*Chemical Water Quality*

Chemical water quality constituents were monitored under baseflow and stormflow conditions. Storm event mean concentrations of several chemical constituents were found to be related to both storm size (magnitude and intensity) and basin imperviousness (Bryant 1995; Horner et al. 1996). However, water quality criteria were rarely violated except in the most highly urbanized watersheds (%TIA > 45%). Total phosphorus (TP) and total suspended solids (TSS) also showed similar relationships. Sediment, zinc and lead also indicated a relationship with urbanization, again showing the highest concentrations in the most developed basins, although all were still below sediment quality guidelines. As with other recent studies (Bannerman et al. 1993; Pitt et al. 1995), these findings indicate that chemical water quality of urban streams is generally not significantly degraded at the low impervious levels, but may be a more important factor in streams draining highly urbanized watersheds.

*Instream Salmonid Habitat Characteristics*

Large woody debris (LWD) is a ubiquitous component in streams of the Pacific Northwest. There is no other structural component as important to salmonid habitat, especially in the case of juvenile coho (Bisson et al. 1988). LWD performs critical functions in forested lowland streams, including dissipation of flow energy, streambank protection, streambed stabilization, sediment storage, and providing instream cover and habitat diversity (Bisson et al. 1987; Masser et al. 1988; Gregory et al. 1991). Although the influence of LWD may change over time, both functionally and spatially, its overall importance to salmonid habitat is significant and persistent.

Both the prevalence and quantity of LWD declined with increasing basin urbanization (Figure 6a). At the same time, measures of salmonid rearing habitat, including % pool area, pool size, and pool frequency, were strongly linked to the quantity and quality of LWD in PSL streams. While LWD quantity and quality were negatively affected by urbanization, even many of the natural, undeveloped streams also had a lack of LWD (especially very large LWD). This deficit appears to be a residual effect of historic timber-harvest and "stream-cleaning" activities. Nevertheless, with few exceptions (habitat restoration sites), high quantities of LWD occurred only in streams draining undeveloped basins (%TIA < 5%). It appears that stream restoration in the PSL should include enhancement of instream LWD, including addressing the long-term LWD recruitment requirements of the stream ecosystem.

An intact and mature riparian zone is the key to maintenance of instream LWD (Masser et al. 1988; Gregory et al. 1991). The lack of functional quantities of LWD in PSL streams was significantly influenced by the loss of riparian integrity (Figure 6b). In general, except for restoration sites, higher quantities of LWD were found only in stream-segments with intact upstream riparian corridors. In addition, LWD quality was strongly influenced by riparian integrity. Very large, stable pieces of LWD (greater than 0.5 meter in diameter) were found only in stream segments surrounded by mature, coniferous riparian forests. This natural LWD historically provided stable, long-lasting instream structure for salmonid habitat and flow mitigation (Masser et al. 1988).

**Figure 6a: LWD Quantity and Watershed Urbanization (%TIA) in PSL Streams**

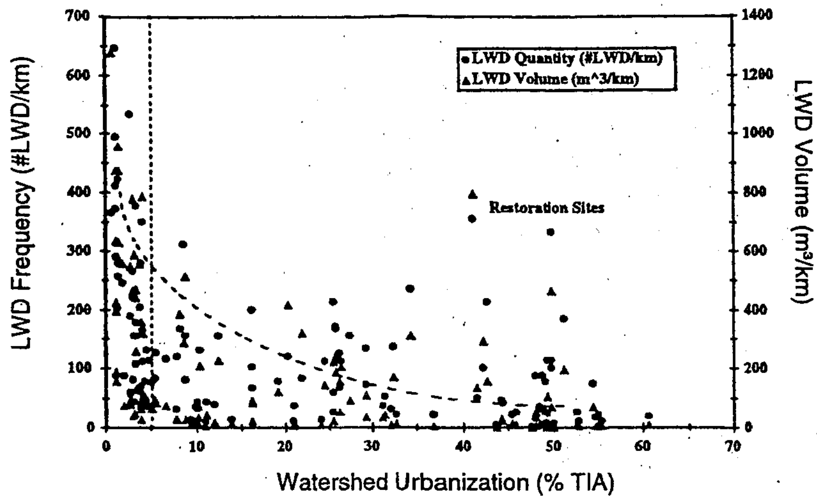
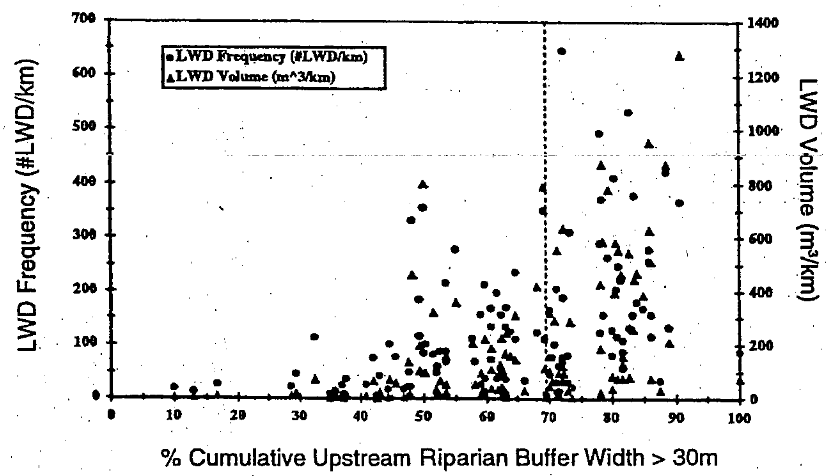



**Figure 6b: LWD Quantity and Riparian Integrity In PSL Streams**



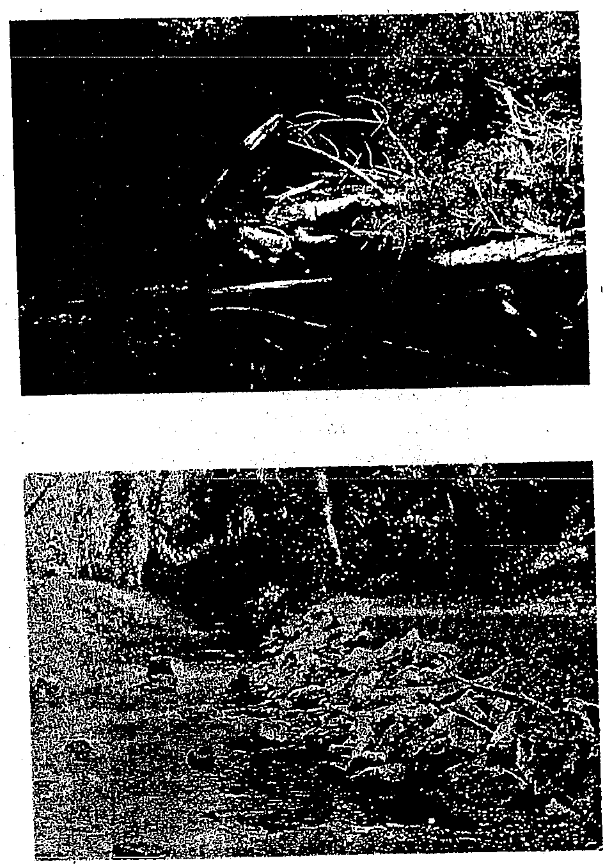

The stream bottom substratum is critical habitat for salmonid egg incubation and embryo development, as well as being habitat for benthic macroinvertebrates. Streambed quality can be degraded by deposition of fine sediment, streambed instability due to high flows, or both. Although, the redistribution of streambed particles is a natural process in gravel-bed streams, excessive scour and aggradation often result from excessive flows. Streambed stability was monitored using bead-type scour monitors installed in salmonid spawning riffles in selected reaches (Nawa and Frissell

1993). Basin urbanization in PSL streams was found to have the potential to cause locally excessive scour and fill. Urban streams in the PSL with gradients greater than 2% and lacking in LWD, were found to be more susceptible to scour than their undeveloped counterparts.

Large Woody Debris (LWD) provides critical habitat in the stream ecosystem.

Streambank erosion was also far more common in urbanized PSL streams than in streams draining undeveloped watersheds. Using a survey protocol similar to Booth (1996), all stream segments were evaluated for streambank stability. Stream segments with >75% of the reach classified as stable were given a score of 4. Between 50% and 75% stable banks were scored as a 3, 25-50% as a 2, and <25% as a 1. Artificial streambank protection (riprap), shown in the photo in the right panel below, was considered a sign of bank instability and graded accordingly. Only two undeveloped, reference (%TIA < 5%) stream segments had a stability rating less than 3. In the 5-10% basin imperviousness range, streambank ratings were generally ranked 3 or 4. When the sub-basin impervious area was between 10-30%, there was a fairly even mixture of streambank conditions from stable ar natural to highly eroded or artificially "protected." Above 30% TIA, there were no segments with a streambank stability rating of 4 and very few with a rating of 3. These outliers were found only in segments with intact and wide riparian corridors. Artificial streambank protection (riprap) was a common feature of all highly-urbanized streams. Overall, the streambank stability rating was inversely correlated with cumulative upstream basin %TIA and even more closely correlated with development within the segment itself, perhaps reflecting the local effects of construction and other human activities. Streambank stability is also influenced by the condition of the riparian vegetation surrounding the stream. In this study, the streambank stability was related to the width of the riparian buffer and inversely related to the number of breaks in the riparian corridor. While not completely responsible for

**Figure 7: Large Woody Debris in Undisturbed and Urbanizing Streams**



*Large woody debris (LWD) is an important structural element of undisturbed Puget Sound lowland streams (top panel). Urbanizing watersheds have much lower levels of LWD within the stream (bottom panel).* ***Photographs by Chris May*** the level of streambank erosion, basin urbanization and loss of riparian vegetation, contribute to the instability of streambanks.

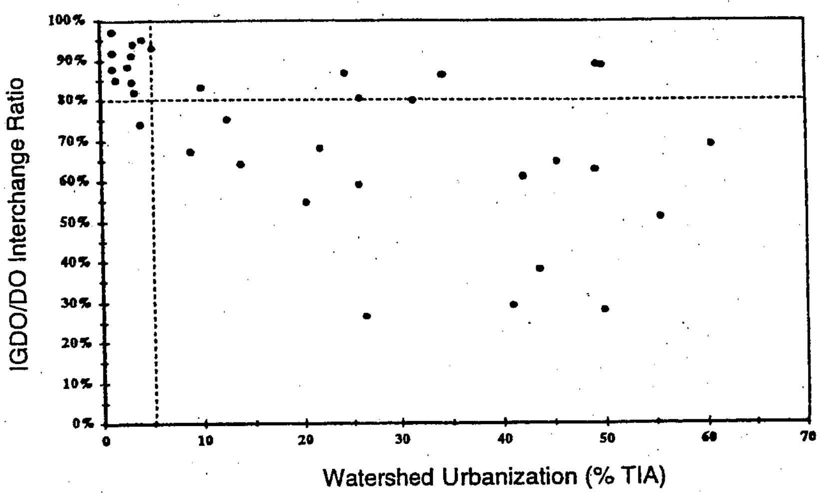
Results of fine sediment sampling (McNeil method) indicated that urbanization can result in degradation of streambed habitat. Fine sediment levels (% fines) were related to upstream basin urban development, but the variability, even in undeveloped reaches, was quite high (Wydzga 1997). Nevertheless, percent fines did not exceed 15% until %TIA exceeded 20%. In the highly urbanized basins, the percent fines were consistently > 20% except in higher gradient reaches where sediment was presumably flushed by high stormflows.

The intragravel dissolved oxygen (IGDO) was also monitored as an integrative measure of the deleterious effect of fine sediment on salmonid incubating habitat. A significant impact of fine sediment on salmonids is the degradation of spawning and incubating habitat (Chapman 1988). The incubation period represents a critical and sensitive phase of the salmonid life cycle. A high percentage of fine sediment can effectively clog the interstitial spaces of the substrata and reduce water flow to the intragravel region. This can result in reduced levels of IGDO and a buildup of metabolic wastes, leading to even higher mortality. Elevated fine sediment levels can also have various sub-lethal effects on developing salmonids which may reduce the odds of survival in later life stages (Steward 1983).

While low IGDO levels are typically associated with fine sediment intrusion into the salmonid redd, local conditions can have a strong influence on intragravel conditions as well as the distribution of fine sediment (Chapman 1988). Spawning salmonids themselves can also reduce the fine sediment content of the substrata, at least temporarily. Measurement of instream dissolved oxygen (DO) coincident with IGDO allowed for the calculation of a IGDO/DO interchange ratio (Figure 10). In all but one case, the mean interchange ratio was > 80% in the undeveloped streams. Once TIA increased above 10%, a great majority of the reaches had a mean interchange ratio well below 80% (as low as 30%). While these DO levels are not lethal, low IGDO levels during embryo development can reduce survival to emergence (Chapman 1988). Several urbanized stream-segments had unexpectedly high (>80%) IGDO concentrations (Figure 8). All of these segments were associated with intact riparian corridors and upstream riparian wetlands. Generally, these reaches also had stable streambanks and adequate levels of instream LWD.

Coho salmon rely heavily on small lowland streams and associated off-channel wetland areas during their rearing phase (Bisson et al. 1988). They are the only species of salmon that overwinter in the small streams of the PSL. Cutthroat trout are commonly found in almost all small streams in the Pacific Northwest. Cutthroat and coho are sympatric in many small streams and as such are potential competitors (adult cutthroat also prey on juvenile coho). In general, habitat, rather than food, is the limiting resource for most salmonids in the region (Groot and Margolis 1991).

**Figure 8: Relationship Between Urbanization and Mean Intragravel Dissolved Oxygen (IGDO) Instream Dissolved Oxygen Ratio in PSL Streams**




*The 16 DO/DO Ratio is an indicator of sediment intrusion into spawning redds.*

In urban streams of the PSL, rearing habitat appears to be limiting. This study found all but the most pristine (%TIA < 5%) lowland streams had significantly less than 50% of stream habitat area as pools. In addition, the fraction of cover on pools decreased in proportion to sub-basin development. Coho rear primarily in pools with high habitat complexity, abundant cover, and with LWD as the main structural component (Bisson et al. 1988). Urbanization and loss of riparian forest area significantly reduced pool area, habitat complexity, and LWD in PSL streams.

Intragravel dissolved oxygen was used as an indicator of spawning habitat quality in streams.

*Biological Integrity*

The biological condition of the benthic macroinvertebrate community was expressed in terms of a multi-metric PSL Benthic Index of Biotic Integrity (B-IBI) developed by Kleindl (1995) and Karr (1991). The abundance ratio of juvenile coho salmon to cutthroat trout (Lucchetti and Fuerstenberg 1993) was used as a measure of salmonid community integrity. Figure 9 shows the direct relationship between urbanization (%TIA) and biological integrity, using both measures. Only undeveloped reaches (%TIA < 5%) exhibited an B-IBI of 32 or greater (45 being the maximum possible score). There also appears to be rapid decline in biotic integrity with the onset of urbanization. At the same time, it appears unlikely that streams draining highly



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**Figure 9: Relationship Between Instream Habitat Quality and `iotic Integrity**

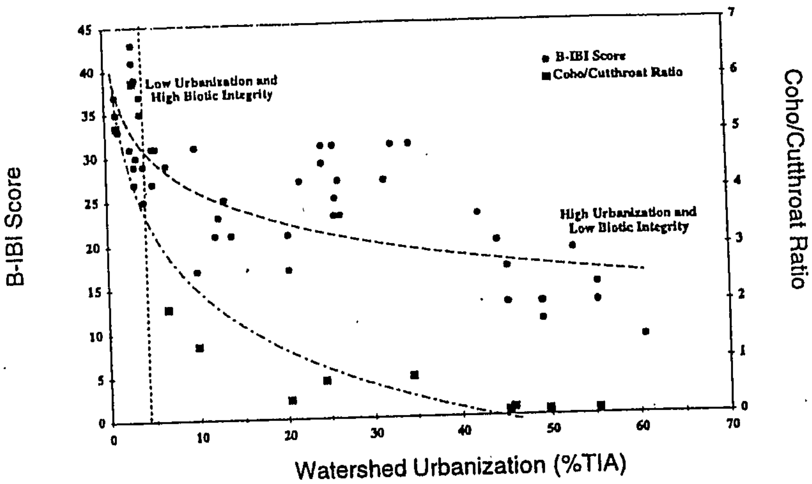
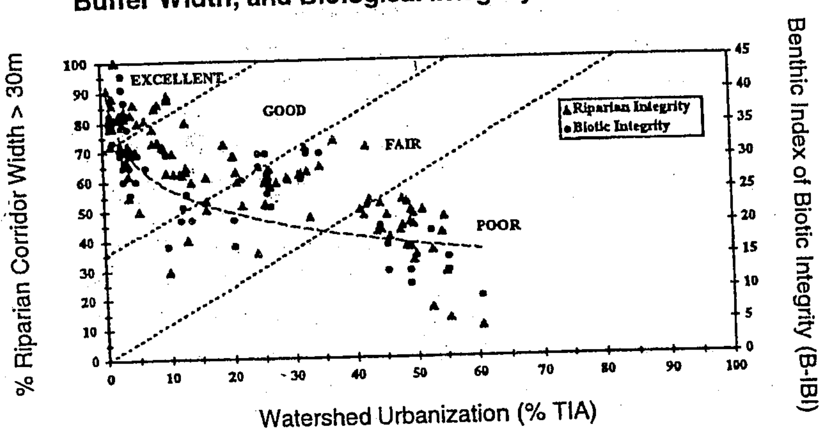



**Figure 10: Relationship Between Basin Development, Riparian Buffer Width, and Biological Integrity in PSL Streams**




urbanized sub-basins could maintain a B-IBI greater than 15 (minimum B-IBI is 9). B-IBI scores between 25 and 32 were associated with reaches having a %TIA < 10%, with eight notable exceptions (Figure 9). These eight reaches had sub-basin %TIA values in the 25-35% (suburban) range and yet each had a much higher biological integrity than other streams at this level of development. All eight had a large upstream fraction of development. All eight had a large upstream fraction of intact riparian wetlands and all but one had a large upstream fraction of wide riparian buffer (> 70% of the stream corridor with buffer width > 30 m = 100 feet). These observations indicate that maintenance of a wide, natural riparian corridor may mitigate some of the effects of watershed urbanization.

Urbanization also appears to alter the relationship between juvenile coho salmon and cutthroat trout. In this study, coho tended to dominate in undeveloped (%TIA < 5%) streams, while cutthroat were more tolerant of conditions found in urbanized streams. In eleven study streams where data was available, natural coho dominance (cutthroat:coho ratio > 2) was seen only at very low watershed development levels. Due to the lack of data, a more specific development threshold could not be established. Nevertheless, it is significant that both salmonid and macroinvertebrate data indicate that a substantial loss of biological integrity occurs at a very low level of urbanization. These results confirmed the findings of earlier regional studies.

Given that relationships were identified between basin development conditions and both instream habitat characteristics and biological integrity, it is reasonable to hypothesize that similar direct associations exist between physical habitat and biological integrity. As a general rule, instream habitat conditions (both quantity and quality) correlated well with the B-IBI and the coho:cutthroat ratio. Measures of spawning and rearing habitat quality were closely related to the coho:cutthroat ratio. As might be expected, measures of streambed quality were also closely related to the B-IBI (benthic macroinvertebrates). Chemical water quality may also influence aquatic biota at higher levels of watershed urbanization.

In addition to the quantitative habitat measures, a multi-metric Qualitative Habitat Index (QHI) was also developed for PSL streams. This index assigns scores of poor (1), fair (2), good (3), and excellent (4) to each of 15 habitat-related metrics, then sums all 15 metrics for a final reach-level score (minimum score of 15 and maximum score of 60). The QHI is similar in design to that which is used in Ohio (Rankin 1989) and as part of the U.S. EPA Rapid Bioassessment Protocol (Plafkin et al. 1989). As was expected, biological integrity was directly proportional to instream habitat quality. Coho dominance is consistent with a B-IBI > 33 and a QHI > 47; conditions found only in natural, undeveloped streams. These results were consistent with the findings of a similar study in Delaware (Maxted et al. 1994). The QHI has the advantage of being simpler (less costly) than more quantitative survey protocols, but may not meet the often rigorous requirements of resource managers. However, as a screening tool, it certainly has merit.

A major finding of this study was that wide, continuous, and mature-forested riparian corridors appear to be effective in mitigating at least some of the cumulative effects of adjacent basin development. Using the B-IBI as the primary measure of biological integrity, Figure 10 illustrates how the combination of riparian buffer condition and basin imperviousness explains much of the variation in stream quality. These observations suggest a set of possible stream quality zones similar to those proposed by Steedman (1988). Excellent (natural) stream quality requires a low leve' of watershed development and a substantial amount intact, high-quality riparian corridor. If a "good" or "fair" stream quality is acceptable, then greater development may be possible with an increasing amount of protected riparian buffer required. Poor stream quality is almost guaranteed in highly urbanized watersheds or where riparian corridors are impacted by human activities such as development, timber-harvest, grazing, or agriculture. Because of the mixture of historical development practices and resource protection strategies included in this study, it was difficult to make an exact judgment as to how much riparian corridor is appropriate for each specific development scenario. More intensive research is needed in this area.

## Summary

Results of the PSL stream study have shown that physical, chemical, and biological characteristics of streams change with increasing urbanization in a continuous rather than threshold fashion. Although the patterns of change differed among the attributes studied and were more strongly evident for some than for others, physical and biological measures generally changed most rapidly during the initial phase of the urbanization process as %TIA exceeded the 5-10% range. As urbanization progressed, the rate of degradation of habitat and biologic integrity usually became more constant. There was also direct evidence that altered watershed hydrologic regime was the leading cause for the overall changes observed in instream physical habitat conditions.

Water quality constituents and metal sediment concentrations did not follow this pattern. These variables changed little over the urbanization gradient until imperviousness (%TIA) approached 40%. Even then, water column concentrations did not surpass aquatic life criteria, and sediment concentrations remained far below freshwater sediment guidelines. Once urbanization increased above the 50% level, most pollutant concentrations rose rapidly, and it is likely that the role of water and sediment chemical water quality became more important biologically.

It is also apparent that, for almost all PSL streams, large woody debris quantity and quality must be restored for natural instream habitat diversity and complexity to be realized. Of course, prior to undertaking any habitat enhancement or rehabilitation efforts, the basin hydrologic regime must be restored to near-natural conditions. Results suggest that resource managers should concentrate on preservation of high-quality stream systems through the use of land-use controls, riparian buffers, and protection of critical habitat. Enhancement and mitigation efforts should be focused on watersheds where ecological function is impaired but not entirely lost.

Biological community alterations in urban streams are clearly a function of many variables representing conditions in both the immediate and more remote environment. In addition to urbanization level, a key determinant of biological integrity appears to be the quantity and quality of the riparian zone available to buffer the stream ecosystem, in some measure, from negative influences in the watershed (Figure 10). Instream habitat conditions also had a significant influence on instream biota. Streambed quality, including fine sediment content and streambed stability, clearly affected the benthic macroinvertebrate community (as measured by the B-IBI). The composition of the salmonid community was also influenced by a variety of instream physio-chemical attributes. In the PSL region, management of all streams for coho (and other sensitive salmonid species) may not be feasible. Management for cutthroat trout may be a more viable alternative for streams draining more highly urbanized watersheds. The apparent linkage between watershed, riparian, instream habitat, and biota shown here supports management of aquatic systems on a watershed scale. The accompanying box outlines some key watershed management recommendations for PSL streams.

> Stream indicators declined continuously with urbanization, but the most rapid change was seen at 5 to 10% impervious cover.

The findings of this research indicate that there is a set of necessary, though not by themselves sufficient, conditions required to maintain a high level of stream quality or ecological integrity (physical, chemical, and biological). If maintenance of that level is the goal, then this set of enabling conditions constitutes standards that must be achieved if the goal is to be met. For the PSL streams, imperviousness must be limited (< 5-10 %TIA), unless mitigated by extensive riparian corridor protection and BMPs. Downstream changes to both the form and function of stream systems appear to be inevitable unless limits are placed on the extent of urban development. Stream ecosystems are not governed by a set of absolute parameters, but are dynamic and complex systems. We cannot "manage" streams, but instead should work more as "stewards" to maintain naturally high stream quality. Preservation and protection of high-quality resources, such as salmon, should be a priority. The complexity and diversity of salmonid life cycles and our limited understanding of them, merits additional caution in our efforts to mediate the effects of urbanization in stream environments. Engineering solutions in urban streams have utility in some situations, but in most cases cannot fully mitigate the effects of development. Rehabilitation and enhancement of aquatic resources will almost certainly be required in all but the most pristine watersheds.

### PSL Stream Study Recommendations for Ensuring Natural Stream Quality

**Land Use and Transportation**

- Reduce watershed imperviousness, especially targeting transportation-related surfaces and compacted pervious areas.
- Preserve at least 50% of the total watershed surface area as natural forest cover.
- Maintain urbanized stream system drainage-density to within 25% of pre-development conditions.
- Replace culverted road-crossings with bridges or arched culverts with natural streambed material.

**Riparian Zone**

- Limit stream crossings by roads or utility lines to less than 2 per km of stream length and strive to maintain a near-continuous riparian corridor.
- Ensure that at least 70% of the riparian corridor has a minimum buffer width of 30 m and utilize wider (100 m) buffers around more sensitive or valuable resource areas.
- Limit encroachment of the riparian buffer zone through education and enforcement (< 10% of the riparian corridor should be allowed to have a buffer width < 10 m).
- Protect and enhance headwater wetlands and off-channel riparian wetland areas as natural stormwater storage areas and valuable aquatic habitat resources (buffers).
- Actively manage the riparian zone to ensure a long-range goal of at least 60% of the corridor as mature, native coniferous forest.

**Stormwater and Water Quality**

- Allow no development in the active (100-year) floodplain area of streams. Allow the stream channel freedom of movement within the floodplain area.
- Continuously monitor streamflow and maintain 2-year stormflow/baseflow discharge ratio much less than 20.
- Allow no stormwater outfalls to drain directly to the stream without first being treated by stormwater quality and quantity control facilities.
- Retrofit existing BMPs or replace with regional (sub-basin) stormwater control facilities with the goal of restoring the natural hydrologic regime.
- Adopt a set of regionally-specific stream assessment protocols including standardized biological sampling.
- Tailor monitoring of instream physical conditions to the specific situation. Habitat surveys should include a measure of rearing habitat (LWD and/or pools) and a measure of spawning/incubating habitat (% fines and/or IGDO); standard channel morphological characteristics should be measured; scour monitoring can be used to evaluate local streambed stability in association with specific development activity.

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**Metric to English Conversion Table**

| Unit | To Convert | Multiply By | To Obtain |
|---|---|---|---|
| Length | km | .621 | mi |
| Length | meters | 3.281 | ft |
| Area | $km^2$ | 247.1 | acres |
| Area | $km^2$ | .386 | $mi^2$ |
| Proportion | $km / km^2$ | 1.609 | $mi / mi^2$ |

# ADJUSTMENTS OF THE FLUVIAL SYSTEM

DALLAS D. RHODES
GARNETT P. WILLIAMS
*editors*

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# HYDRAULIC GEOMETRY, STREAM EQUILIBRIUM AND URBANIZATION

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## ABSTRACT

Hydraulic geometry variables are not only interrelated to each other but also depend upon climate, geology, soils, land use, and vegetation. These are first-order variables that determine the hydrologic and sedimentologic regimen of the stream and, thus, the morphology. Whenever any of these factors change, effects are felt in the dynamics and morphology of the system. Man's activities may cause significant changes in fluvial systems. Many authors have documented the hydrologic and sedimentologic alterations in streams caused by urbanization.

Studies in urbanizing watersheds near Pittsburgh, PA, and Binghamton, NY, indicate changes in hydraulic geometry brought about by urbanization. The initial effect of increased discharge resulting from development in a basin is proposed to be an increase in velocity of flow. Channel enlargement is a secondary result of the changed hydrologic regimen. There is a tendency for an accelerated rate of increase in channel cross-sectional area with increased basin area of urbanized rivers. An inflection point indicates a threshold where peak velocity is capable of increasing the channel size. Thus, there is a lag between changes in land use and final morphologic adjustment of the channel. The time lag is determined by the relation of velocity increase to the ability of the stream to move bed and/or bank material.

Readjustment of a stream to changes in its regimen are governed by natural laws of dynamics and morphologic response.

## INTRODUCTION

The morphology and hydraulic geometry characteristics of a stream are not only interrelated to each other, but are also dependent upon variables such as climate, lithology, topography, soil, land use, and vegetation (fig. 1). These first-order independent elements determine the discharge and sediment load, which are second-order factors. All of these variables and subvariables interact through a complicated feedback mechanism that determines the morphologic configuration of a river and the processes and rates of their operation in any individual watershed (fig. 2). Because the hydrology and other environmental conditions may vary in time and space over a river basin, the whole river system is dynamic, changing both temporally and spatially.

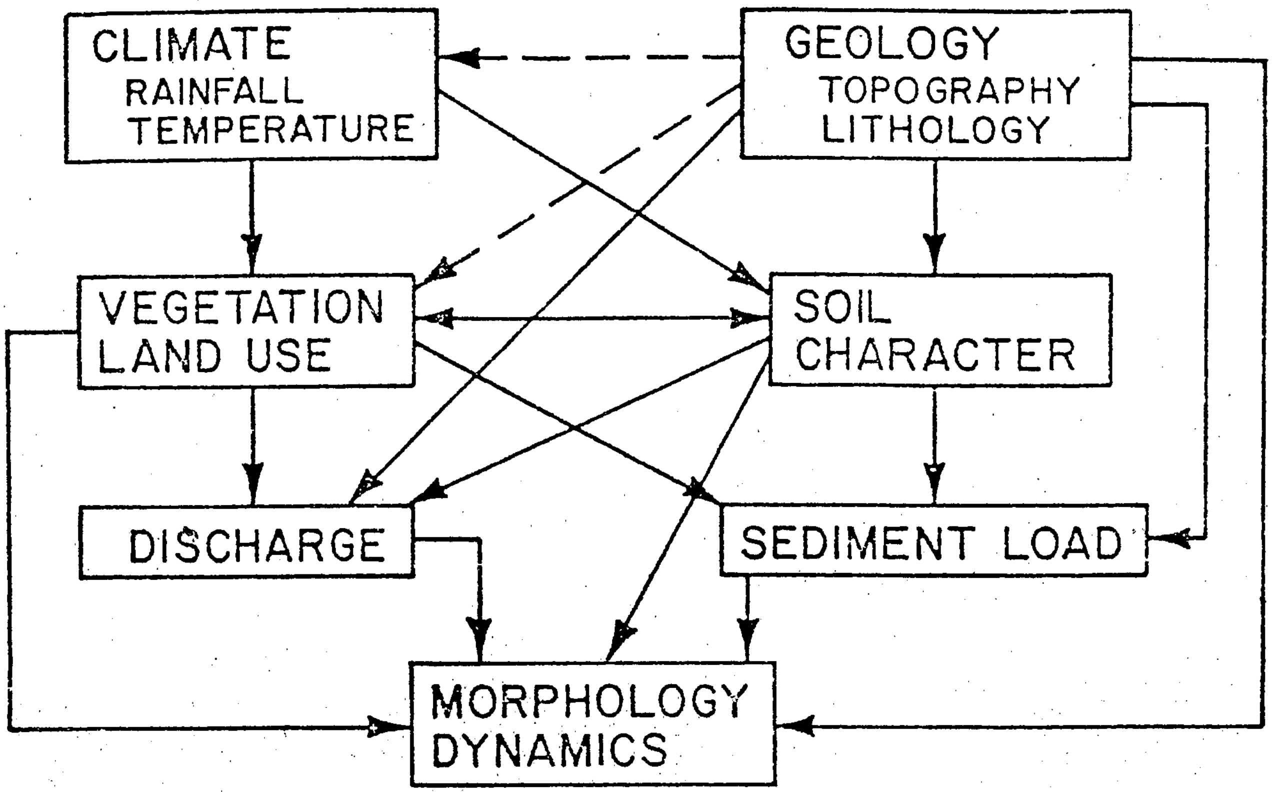
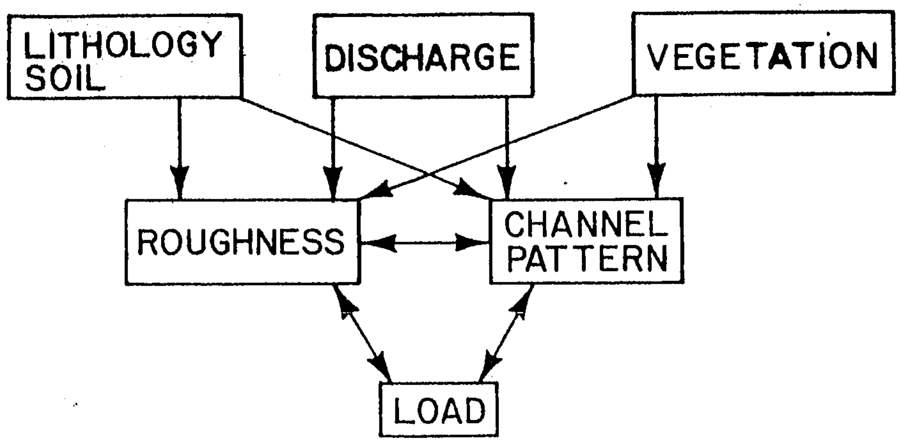



*Figure 1. Factors influencing stream morphology and dynamics (from Morisawa and Vemuri, 1976).*

Over a long period of time, each river seeks to achieve a natural adjustment of its hydraulics and morphology to the prevailing discharge and sediment load as determined by the general environment of its basin. This principle of adjustment means the river reaches an equilibrium between energy and load under the specific environmental conditions of the watershed. Whenever any of the conditions change, there is a response in the system that affects the morphology and dynamics.

Man's activities cause important disturbances in watersheds. In changing land use during urbanization, most of the first order, independent variables of figure 1 are altered. In turn, the second-order factors of hydrology and load are changed. Numerous studies have shown the effects of urbanization on the hydrology of watersheds. Specifically, land use changes and the disruption of the environment result in larger and more frequent floods (Carter, 1960; Wilson, 1967; Leopold, 1968; and Anderson, 1970), more total surface runoff (Harris and Rantz, 1964; Seaburn, 1969; and Miller and Viessman, 1972), and decreased time lag in runoff response (Brater and Suresh, 1969). The effects on sediment load have been studied by Guy (1970), Wolman (1967) and Knott (1973). A corresponding adjustment in the morphology of the stream channel is to be expected. Hammer (1972), Leopold (1973), Robinson (1976), and LaFlure (1978) are among those who have documented changes in stream channel morphology that resulted from urbanization.

Several basic principles must be considered in analyzing morphologic response in river systems. First, the system is integrated so that an environ-



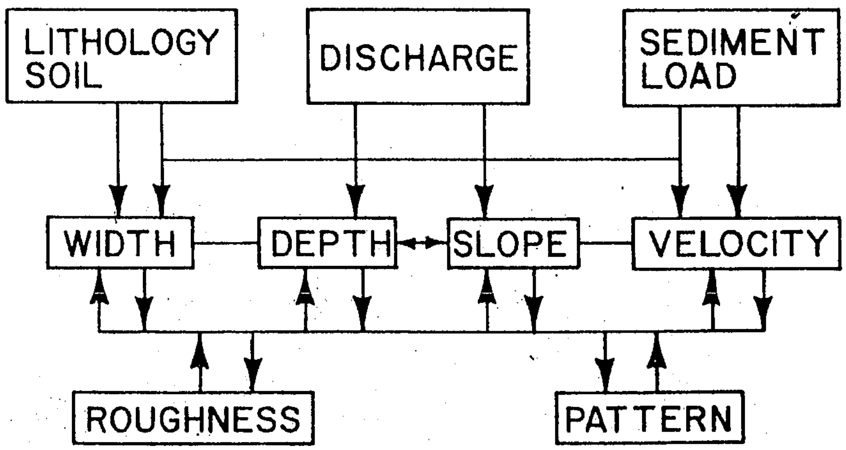




*Figure 2. Factors affecting channel morphology (from Morisawa and Vermuri, 1976).*

mental change in one part of a watershed is felt elsewhere in the system. For example, Smith (1973) gave examples of both upstream and downstream controls on aggradation of two rivers in Canada. Second, the system in balance is self-regulatory, so that a change necessitates response. The most important concept illustrated by figures 1 and 2 is that "everything affects everything else." And because response is generally negative (unless change continues), a new equilibrium will be reached in which a changed morphology is the outcome of the new conditions. Third, the response to change of the hydrologic and sedimentologic regimen may not necessarily be immediate (Allen, 1974). Schumm (1973) has shown that adjustment may be delayed until a threshold value is reached.

This paper presents examples of changes in hydraulic geometry and stream morphology caused by urbanization in watersheds near Pittsburgh, PA, and Binghamton, NY.

## THE STUDY WATERSHEDS

Three areas--two near Pittsburgh, PA, and one in the Binghamton, NY region--are under study. The first area consists of four watersheds (Squaw Run, Guyasuta Run, Seitz Run, and Powers Run) in the townships of O'Hara and Fox Chapel near Pittsburgh (fig. 3). The second area consists of three basins (Mosside, Dirty Camp, and Abers Creeks) in the town of Monroeville, east of Pittsburgh (fig. 3). Two small basins (Brixius Creek and Fuller Hollow) comprise the New York study area (fig. 4).

Both Pennsylvania areas are on the unglaciated Allegheny Plateau. The areas are underlain by essentially flat-lying Pennsylvanian cyclothem sequences of sandstone, shale, limestone, claystone, and coal units. The broad flat summits of the plateau are dissected by streams that have cut valleys 60-120 m deep. Valley side slopes are generally steep. Although smaller valleys are narrow with limited flat areas, larger tributaries (i.e., Squaw Run and Abers Creek) have wide floodplains.

Climate is humid, with a mean annual precipitation of 1,016 mm and an average annual runoff of 406 mm (Geraghty et al., 1973). The highest discharge generally occurs in March, the lowest in September. Forests are mixed hardwoods, usually covering the valley side slopes. Some farms and open fields are located on the plateau surface. Urbanization has occurred on both the lower floodplains and the broad summits.

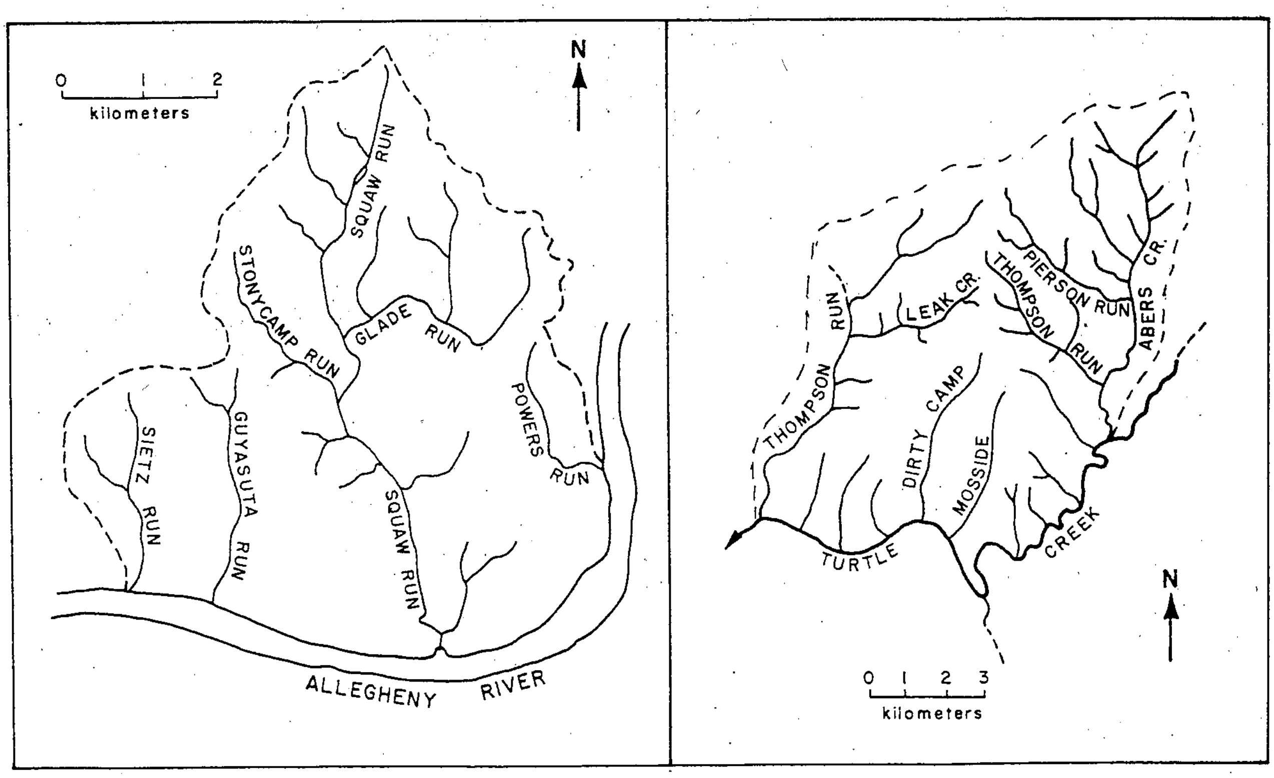



*Figure 3. Pittsburgh area watersheds.*

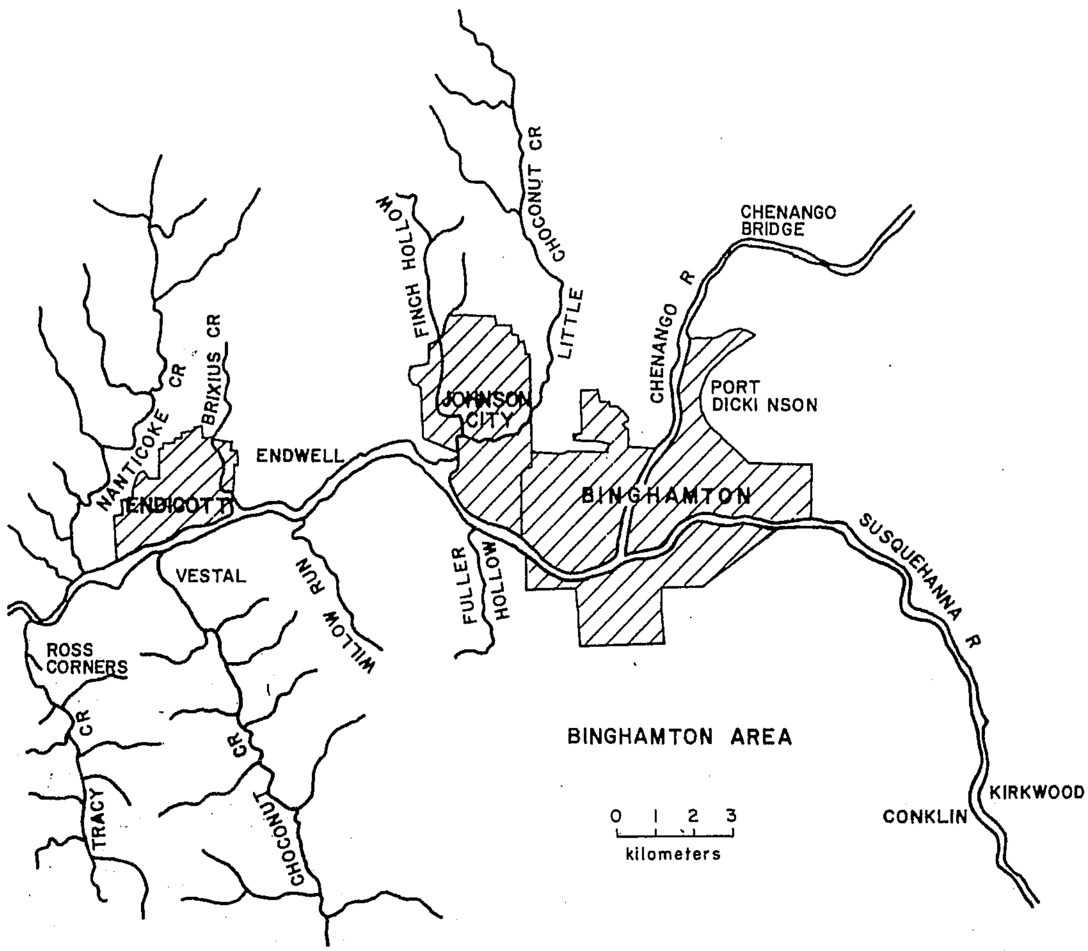



*Figure 4. Binghamton area watersheds.*

Two nearby unurbanized watersheds were chosen for control purposes. Rawlins and Shafer Runs are just north of the Fox Chapel area. These watersheds are natural (2 % urbanized) and served as a basis for comparison of channel enlargement.

The two stream basins under study in the Binghamton area are highly urbanized. Brixius Creek is on the north side of the Susquehanna River in the town of Endicott. Fuller Hollow is located on the south side of the river in the town of Vestal. Both basins are within the glaciated Allegheny Plateau. The bedrock is essentially flat-lying sandstone, siltstone, and shale of Devonian age.

The region has been glaciated, resulting in a topography characterized by smoothed and rounded hills. Relief is of the order of 90-210 m. The major valleys were broadened and deepened by glaciation, and many small tributaries flow in valleys rather large for the present-sized streams. The upper headwaters of both streams drain the till-covered open rolling summits. Middle reaches narrow as the streams cut through bedrock. Lower stretches are wider and terraced as the streams flow over glacio-fluvial deposits.

The Binghamton climate is humid, with 890 mm of rainfall yearly and an annual runoff of 510 mm (Geraghty et al., 1973). High discharges occur in April and low flow in September. Vegetation is mixed hardwood forest with stands of evergreens. Farms and open fields occupy part of the flat divide surface. There are numerous glacial or man-made ponds. Urbanization, which started in the lower watershed, has expanded upward on to the hill-slopes and broad divides.

Table 1 gives some of the physical characteristics of the study basins.

Table 1

Characteristics of Basins Studied

| Watershed | Drainage Area $km^2$ | Max. Relief m | Gradient m/m | % Urban[a] |
|---|---|---|---|---|
| Pittsburgh, PA area | | | | |
| Area 1[b] | | | | |
| Squaw Run | 21.9 | 135 | .015 | 48 |
| Seitz Run | 3.73 | 105 | .038 | 75 |
| Guyasuta Run | 3.21 | 115 | .034 | 64 |
| Powers Run | 2.32 | 90 | .036 | 91 |
| Area 2 | | | | |
| Mosside Creek | 3.47 | 105 | .032 | 37 |
| Dirty Camp Creek | 5.57 | 115 | .023 | 29 |
| Abers Creek | 27.5 | 120 | .020 | 26 |
| Control Basins | | | | |
| Rawlins Run | 4.01 | 90 | .025 | 2 |
| Shafers Run | 4.01 | 90 | .025 | 2 |
| Binghamton, NY area | | | | |
| Area 3 | | | | |
| Brixius Creek | 7.93 | 115 | .023 | 80 |
| Fuller Hollow | 9.89 | 215 | .038 | 25 |

(a) Percent of area greater than 5 % impermeable

(b) Data for Squaw Run, Guyasuta Run, Seitz Run, and Powers Run from LaFlure (1978) and Nelson (1979).

All streams have gravelly pebble beds with some silt and cobbles. Generally the stream banks are of stratified gravel, sand, and silt. Upstream channel banks in the Pittsburgh area watersheds are composed of weathered rock and soil. Binghamton watersheds on till have channel banks of mixed clay, silt, and pebbles or cobbles. All streams studied have stretches where bed and/or banks are cut in bedrock.

The O'Hara-Fox Chapel watersheds (study area one) have been studied over two summers (1977 and 1978) (LaFlure, 1978 and Nelson, 1979). Hydrologic data were obtained from recording gages installed on Squaw and Powers Runs. Measurements of instantaneous discharge and bankfull morphology were made periodically on all O'Hara-Fox Chapel streams during both summers. Bankfull morphology of Rawlins and Shafers Runs was measured by Nelson (1979). Measurements of the Monroeville streams (study area two) were made by Lorraine O'Day and M. Morisawa in the summer of 1978. The Binghamton streams (area three) have been monitored periodically since 1972-73 by Morisawa and her students.

## CHANGES IN HYDRAULIC GEOMETRY AND CHANNEL SIZE

Documentation of changes in the hydrologic regimen of the watersheds under study has been done elsewhere. LaFlure (1978) collected hydrologic data which indicated that urbanization of the river basins in O'Hara-Fox Chapel boroughs has resulted in higher peak flows and increased frequency of overbank flooding. Morisawa and Vemuri (1976) showed that urban development had greatly increased direct storm runoff from Brixius Creek watershed and Fuller Hollow.

The following is a discussion of the hydraulic geometry and morphologic data, comparing adjustments made by the streams of the three areas in response to the augmented discharge.

### Downstream Hydraulic Geometry

In terms of bankfull hydraulic geometry (table 2) each stream responds to the downstream increase in discharge in a distinctive way. In the Pittsburgh area, Guyasuta Run, Squaw Run, Mosside Creek, and Abers Creek accommodate increasing discharge downstream primarily by adjusting the flow velocity, as indicated by the relatively large m-exponent. Seitz and Powers Runs increase in depth (exponent f) downstream more acutely than in either width (b) or velocity (m). Dirty Camp increases its width at a slightly greater rate than its depth in a downstream direction. Powers Run was the earliest developed of these watersheds, has the greatest percentage of its surface greater than 5 % impermeable, and is the smallest. The hydraulic geometry exponents show its channel has enlarged so that velocity change downstream is small in comparison with the other streams.

In the Binghamton area, a number of years of record show how Brixius Creek and Fuller Hollow have changed their modes of adjustment over time. The lower basin of Fuller Hollow was developed in the mid-1960's, and concomitantly, the lower reaches were rerouted and channelized in part. A subdivision was started in the headwaters about 1970. As of 1973 the stream

Table 2

Downstream Hydraulic Geometry

| Watershed | Hydraulic Exponents[a] b | f | m[b] |
|---|---|---|---|
| Squaw Run[c] | 0.17 | 0.34 | 0.49 |
| Guyasuta Run[c] | 0.04 | 0.49 | 0.47 |
| Seitz Run[c] | 0.29 | 0.45 | 0.26 |
| Powers Run[c] | 0.37 | 0.55 | 0.08 |
| Mosside Creek | 0.33 | 0.23 | 0.44 |
| Dirty Camp Creek | 0.44 | 0.38 | 0.18 |
| Abers Creek | 0.38 | 0.03 | 0.59 |
| Fuller Hollow | | | |
| 1973 | 0.05 | 0.32 | 0.63 |
| 1975 | 0.20 | 0.30 | 0.50 |
| 1977 | 0.21 | 0.25 | 0.54 |
| 1978 | 0.54 | 0.05 | 0.41 |
| 1979 | 0.53 | 0.06 | 0.41 |
| Brixius Creek | | | |
| 1973 | 0.30 | 0.56 | 0.14 |
| 1975 | 0.03 | 0.65 | 0.32 |
| 1979 | 0.05 | 0.49 | 0.46 |

(a) $W \propto Q^b$, $D \propto Q^f$ and $V \propto Q^m$.

(b) $m = 1 - (b+f)$

(c) data from LaFlure, 1978

showed a very high rate of increase in velocity downstream. Both f and m values have decreased from 1973 to 1979, as urbanization has progressed. On the other hand, b has increased over this time. All the exponents were fairly stable during 1978-79. The present mode of adjustment is by a high rate of increase in width downstream, a somewhat lower (but still high) rate of increase in velocity downstream, and very little change in depth.

The lower part of Brixius Creek watershed is highly impermeable, being covered by industrial and commercial enterprises and high-density housing. After 1973 development slowly extended along the western edge of the basin on the upper slopes and divide. As of 1973 adjustment in a downstream direction was made primarily by a high increase in the depth exponent. With the subsequent development of the middle and upper watershed area, the m exponent has increased, b decreased greatly, while f increased and then decreased (but still remains high).

The downstream hydraulic geometry effects are highly complex, as the manner of adjustment may vary from station to station. This is partly because of individual station environment and partly because the effects of increased runoff may be felt at one station and not at another, depending on where in the watershed urbanization is taking place. At-a-station hydraulic geometry can be used to show adjustments at particular cross sections.

At-A-Station Hydraulic Geometry

Although there are definite downstream trends in the hydraulic geometry (fig. 5), adjustment varies from one transect to another on these small streams because station response to change in discharge is a result of the complex interaction of hydrology, hydraulics, and the comparative resistance of bed and bank material. In the Pittsburgh area this is exemplified by the 1977 Squaw Run at-a-station hydraulic geometry (table 3). Three stations (10, 4, and 6) adjust to increasing discharge primarily by a relatively high rate of velocity increase. Basins above these stations have undergone recent development. Four stations (1, 3, 5, and 7) divide adjustment to increasing discharge approximately equally among the channel size parameters (width and depth) and velocity, i.e., two-thirds of the change is in channel size and one-third in velocity. Station 2, below an impoundment, has a high f-value; station 8, at a river bend, shows major adjustments in width and depth. Station 9, on the floodplain above the mouth, has an extremely high rate of change in width with increasing flow, a high change in depth and a decreasing rate of flow at high discharges with backwater effects.

Figure 6 shows the difference in channel behavior before and after a storm at transect 8 on Squaw Run. The hydraulic geometry trends are quite different after the storm of July 7, 1977, than before it. Although the storm itself was a minor rainfall event, the stream responded to the storm runoff by eroding its bed and deepening its channel (fig. 7). With the new channel configuration the hydraulic geometry variables changed.

That this event is common as the stream tries to adjust during watershed development is further substantiated by data from Fuller Hollow (table 4). This transect is located just below the College Park subdivision in the headwaters, where development began in 1970. The hydraulic geometry variables indicate a high m-value in 1972. The rate of increase of velocity with discharge (m) decreased from 1972 to 1975, and the stream was tending towards a more equable distribution of effect among the hydraulic variables by 1975. Then another spurt of

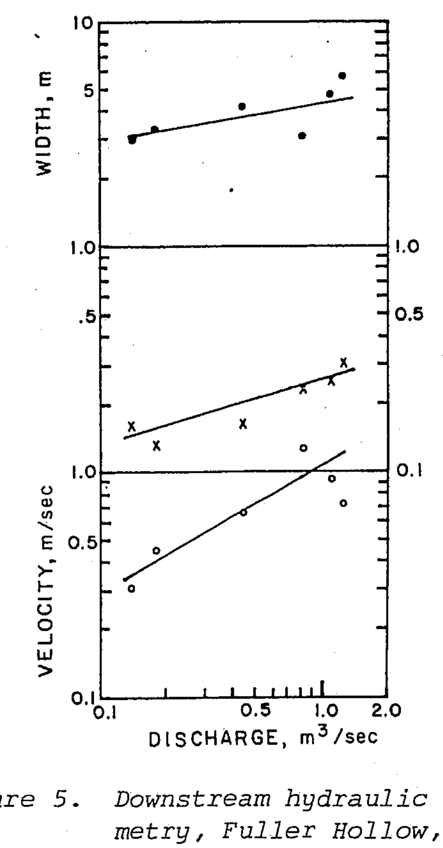



*Figure 5. Downstream hydraulic geometry, Fuller Hollow, 1975.*

Table 3

At-A-Station Hydraulic Geometry[(a)], Squaw Run, 1977

| Station | Hydraulic Exponents b | f | m[(b)] | Comments |
|---|---|---|---|---|
| 1 | .16 | .49 | .35 | Below a tributary, older low density housing |
| 2 | .25 | .63 | .12 | Below a small reservoir |
| 10 | .11 | .23 | .66 | Below a tributary, recent housing, floodplain narrow |
| 3 | .11 | .49 | .40 | Below a major tributary, recent urbanization |
| 4 | .06 | .42 | .52 | Below a major tributary, floodplain narrows |
| 5 | .20 | .43 | .37 | Small tributary, old development |
| 6 | .23 | .26 | .51 | Floodplain, recent development |
| 7 | .32 | .35 | .33 | Floodplain |
| 8 | .45 | .45 | .10 | Floodplain, meander bend |
| 9 | .84 | .41 | -.25 | Above mouth |

(a) data from LaFlure (1978)

(b) $m = 1 - (b+f)$

development in 1976-77 resulted in a rise in the rate of velocity increase. Concomitantly, there was an increase in b and a drastic decrease in f.

These two detailed at-a-station examples suggest morphologic adjustments are still in a state of flux. The at-a-station effect from increased discharge with urbanization apparently begins with an increase in velocity. This seems a viable proposition, especially if the bed and banks are highly resistant. Augmented velocity raises the flow competency at the station and this, in turn, results in an increase in channel size (fig. 8). Enlargement can take place as deepening or widening or both, depending on local bed and bank conditions. Enlargement causes a decrease in velocity so that in time the stream achieves a new equilibrium at the transect, whereby velocity is just that required to maintain a stable channel configuration. However, under continuous change (i.e., continuous development and augmentation of discharge) the stream response continues to change, and this is reflected in changing hydraulic geometry variables.

## Channel Enlargement

An effort was made to determine the magnitude of the changes in channel morphology in these watersheds. Because only a limited field season was available for the Pittsburgh watersheds, better accuracy was attempted by using basin area to the transect in place of a calculated bankfull discharge. The regression exponent, e, in the power relation between bankfull channel cross-sectional area (the dependent variable) and basin area to the transect (independent variable), was calculated for all watersheds (table 5). In addition, the channel enlargement ratio, $R_e$, the ratio of actual increase in cross-section size to the enlargement under natural conditions, was calculated. Because all the watersheds under study were already urbanized, two nearby streams, Rawlins and Shafers Runs were used as controls in the Pittsburgh area. These two watersheds are contiguous to the Fox Chapel - O'Hara basins and similar to them environmentally, except that they are undeveloped. The 1975 cross-sections of both streams were used as controls for Fuller Hollow and Brixius Creek basins. Although the 1975 cross-sections may have been enlarged by urbanization, they can still serve as a basis for comparison of further enlargement.

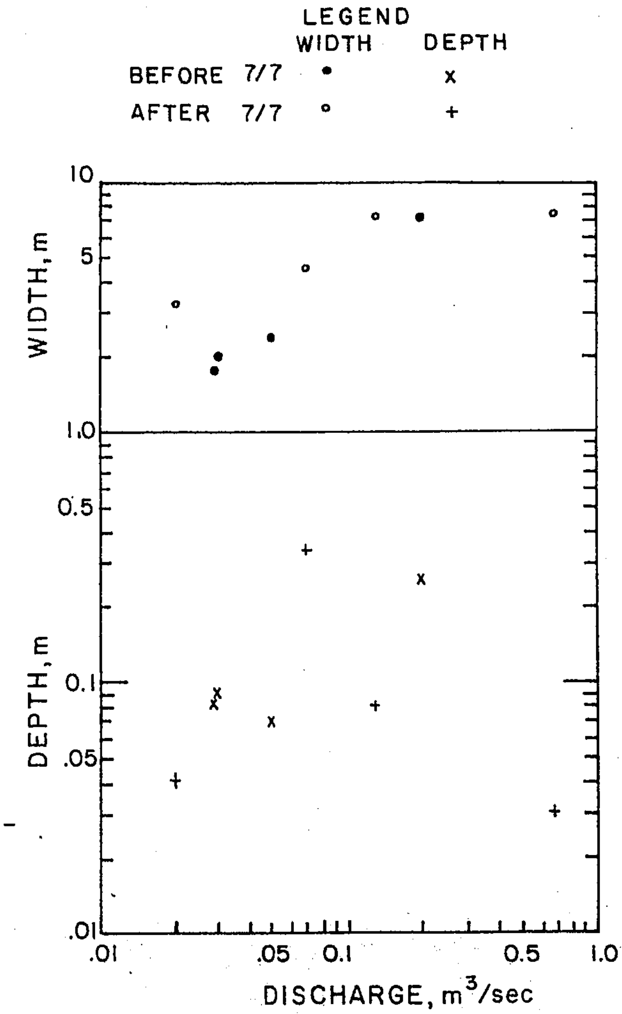



*Figure 6. Hydraulic geometry of transect 8, Squaw Run, before and after the storm of July 7, 1977 (data from LaFlure, 1978).*

Table 4

At-A-Station Hydraulic Geometry, Fuller Hollow, Binghamton Area

| Year | b | f | m(a) |
|---|---|---|---|
| 1972 | 0.04 | 0.14 | 0.82 |
| 1973 | 0.22 | 0.41 | 0.37 |
| 1975 | 0.24 | 0.42 | 0.34 |
| 1977 | 0.38 | 0.05 | 0.57 |

(a) $m = 1 - (b+f)$

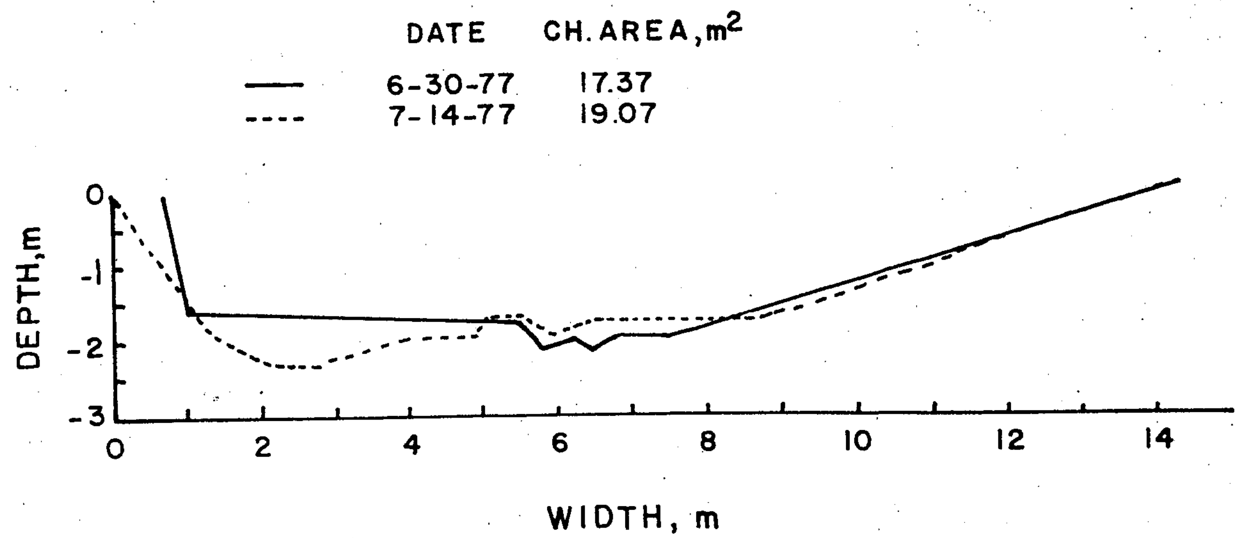



*Figure 7. Cross-sections at transect 8, Squaw Run, before and after the storm of July 7, 1977 (after LaFlure, 1978).*

Figures 9 and 10 indicate the relationship of bankfull cross-section area to drainage basin area at the transect for all the watersheds studied. All regressions are significant at the 0.05 level except that for Guyasuta Run where scatter is quite large. Five of the nine watersheds show an increasing rate of channel enlargement in the lower part of the streams.

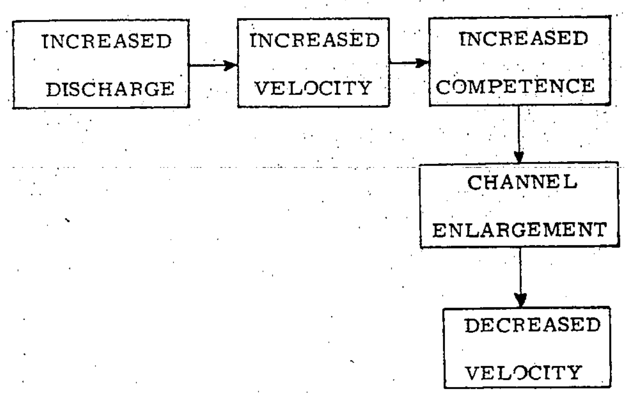



*Figure 8. Proposed response of a stream to increased discharge.*

Measurements on the lower reaches of Brixius Creek could not be made as it is piped underground and only reappears occasionally, in a channelized course. The upper quarter of Fuller Hollow basin is also piped underground beneath College Park. Both of these streams increased substantially in channel size between 1975 and 1979 (fig. 9). Both had a higher rate of enlargement in a downstream direction in 1979 than in 1975. Relations for the upper part of Brixius Creek, shown on figure 9, are linear; relations for the mid and lower stretches of Fuller Hollow indicate an increasing rate of enlargement downstream.

For a given drainage area, e.g. 1.3 km$^2$, the channel cross-section area of Powers Run is larger than that of Squaw Run (fig. 10). Powers Run is much more highly urbanized than Squaw Run. Both, however, have an increasing rate of channel erosion downstream. The control streams, Rawlins and Shafers Runs increase in channel size linearly with increased basin area. The slope of the regression is 0.52. Both Guyasuta and Seitz Runs increase channel size linearly downstream, but at a higher rate than do Rawlins and Shafers Runs.

Table 5

Channel Area Changes with Basin Area and Urbanization

| Watershed | e | $R_e$ (a) | Percent of area > 5 % impermeable |
|---|---|---|---|
| Squaw Run (b) | 0.88 | 1.3 | 48 |
| Powers Run (b) | 0.48 | 6.0 | 91 |
| Seitz Run (b) | 0.87 | 3.4 | 75 |
| Guyasuta Run (b) | 0.67 | 1.95 | 64 |
| Rawlins-Shafer Runs (b) | 0.52 | 1.0 | 2 |
| Mosside Creek | 1.59 | 1.31 | 37 |
| Dirty Camp Creek | 1.50 | 1.13 | 29 |
| Abers Creek | 0.58 | 1.14 | 26 |
| Fuller Hollow | 1.56 | 1.3 | 25 |
| Brixius Creek | 0.86 | 3.30 | 80 |

(a) Reduced to a basin of 2.2 $km^2$

(b) Data from Nelson (1979)

Both Mosside and Abers Creeks have an increasing rate of enlargement downstream. Mosside Creek may be somewhat aberrant because a large part of the middle stretches was altered during road building. The relationship in Dirty Camp Creek, although delineated by a straight line, represents only the upper stretches of the watershed lying in the town of Monroeville. Overall, these graphs indicate an increased rate of channel enlargement as compared to the natural streams, or in the case of Brixius and Fuller Hollow, to enlargement during some previous year.

Channel enlargement ratio plotted against the percent of the watershed that is greater than 5 % impervious indicates a delay in response to development and increased runoff until about 25 % of the area of the watershed has more than 5 % impermeability (fig. 11). Then the rate of downstream channel enlargement gradually increases until approximately 30-40 % of the watershed is greater than 5 % impermeable. After this level of urbanization is achieved the rate of increase in channel size is accelerated. There seems to be a lag in morphologic response of the stream to development until a threshold-value of urbanization is reached. After the threshold is crossed, channel enlargement increases greatly. The threshold of channel enlargement depends upon the percent of the basin that is greater than 5 % impermeable. Nelson (1979) found that 5 % impermeable area best represents both imperviousness and sewering. The lag in morphologic response may be due to the effects proposed previously, i.e., that the initial impact of increased runoff from urbani-

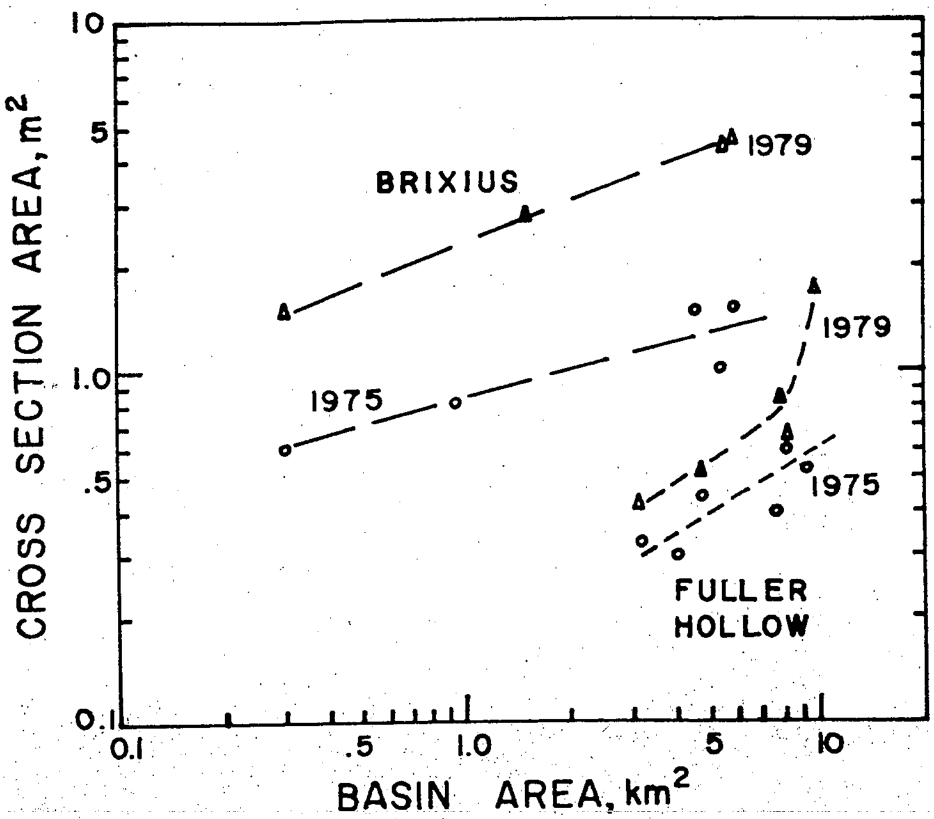


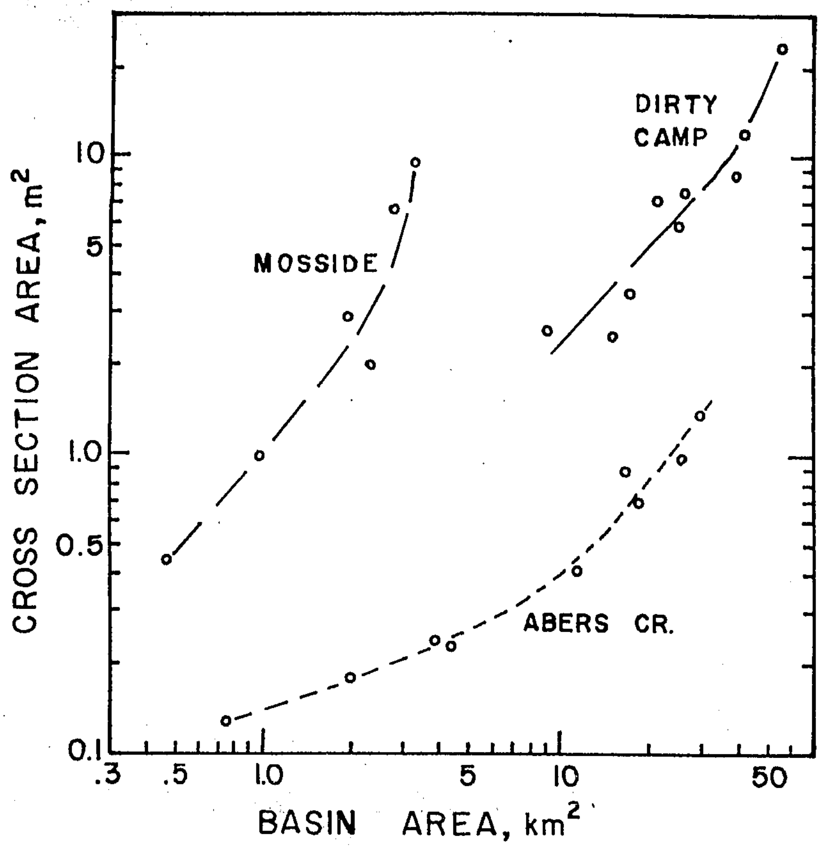

*Figure 9. Channel size (cross-sectional flow area) as a function of upstream drainage area, Brixius Creek and Fuller Hollow, NY.*

zation is increased velocity. When velocity is increased enough for the stream power to overcome resistance of bed and/or banks, enlargement takes place.

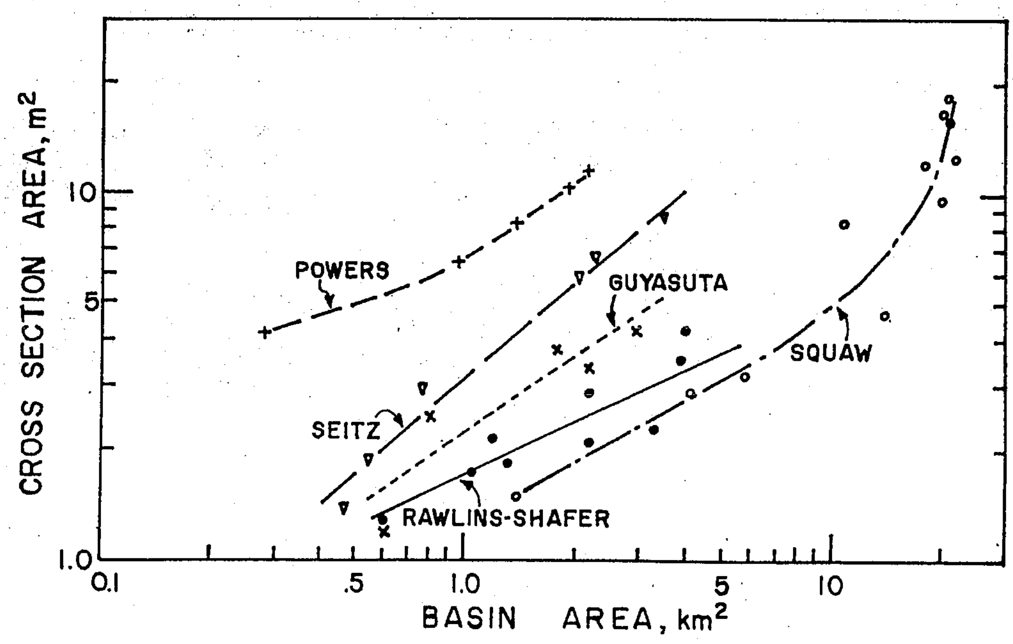
## SUMMARY

Studies in urbanizing watersheds near Pittsburgh, PA, and Binghamton, NY, illustrate the changes in hydraulic variables caused by increased impermeability of basin surface and altered hydrologic regimen. The primary effect of urbanization is increased runoff. The initial hydraulic result appears to be an increase in velocity of flow. This causes increased flooding on the one hand (Leopold, 1968) and channel enlargement on the other (fig. 12). Channel enlargement should result in decreased frequency of over-bank flow and decreased velocity of flow in the channel. This response continues until a new equilibrium is reached, as evidenced by stable channel size and velocity. If change continues in the watershed, the state of equilibrium cannot be attained until urbanization ceases.

There is a tendency for an accelerated increase in channel size with increase of basin area in urban watersheds. The inflection point, at which the rate of enlargement starts to increase, indicates a threshold where flow velocity associated with increased flow magnitude is capable of changing the channel




*(A) Area 2 watersheds*




*(B) Area 1 and control watersheds.*

*Figure 10. Channel size (cross-sectional flow area) as a function of upstream drainage area, Pittsburgh area streams;*

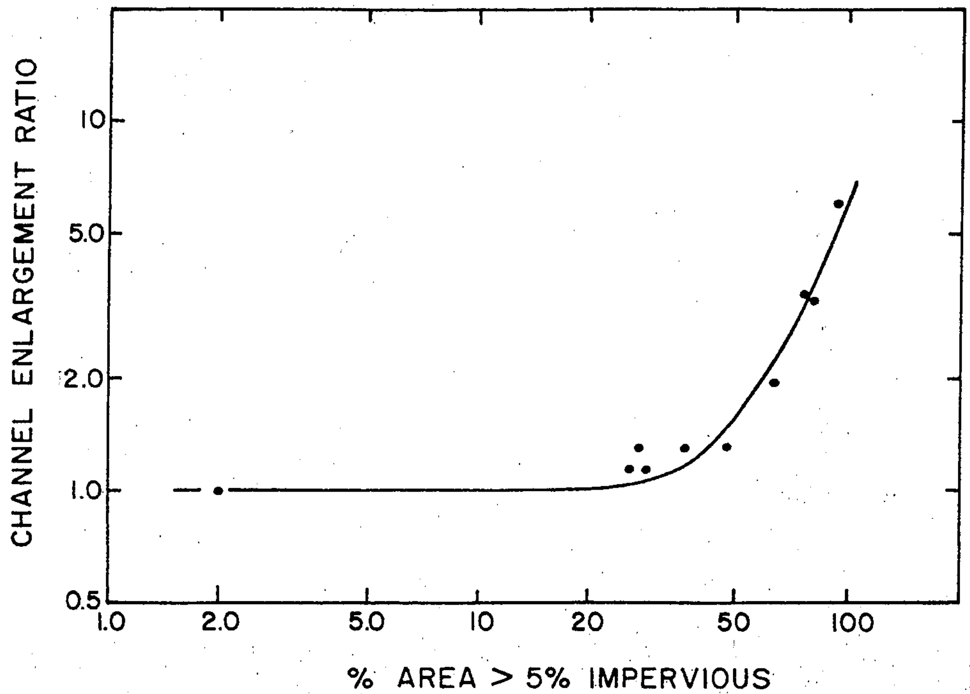



*Figure 11.* *Channel enlargement ratio as a function of percentage of area greater than 5 % impervious.*

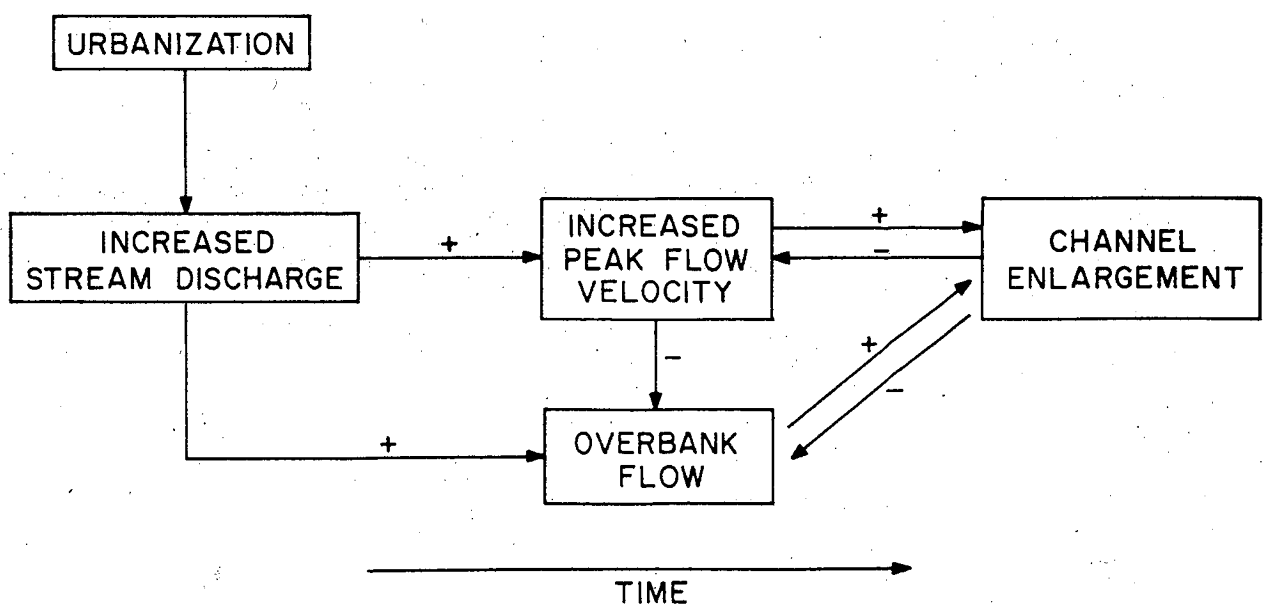



*Figure 12.* *Effects of urbanization on channel enlargement (after LaFlure, 1978).*

size. There is, thus, a time lag between changed hydrologic regimen and channel enlargement. This time lag is determined by the relation of the velocity increase to the power required to remove bed or bank material.

Readjustments of a stream to alterations in its regimen by man are governed by natural laws of dynamics and morphologic response. These laws and their applications can only be completely understood by further research.

## ACKNOWLEDGEMENTS

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# REVIVING URBAN STREAMS: LAND USE, HYDROLOGY, BIOLOGY, AND HUMAN BEHAVIOR[1]

*Derek B. Booth, James R. Karr, Sally Schauman, Christopher P. Konrad, Sarah A. Morley, Marit G. Larson, and Stephen J. Burges*[2]

ABSTRACT: Successful stream rehabilitation requires a shift from narrow analysis and management to integrated understanding of the links between human actions and changing river health. At study sites in the Puget Sound lowlands of western Washington State, landscape, hydrological, and biological conditions were evaluated for streams flowing through watersheds with varying levels of urban development. At all spatial scales, stream biological condition measured by the benthic index of biological integrity (B-IBI) declined as impervious area increased. Impervious area alone, however, is a flawed surrogate of river health. Hydrologic metrics that reflect chronic altered streamflows, for example, provide a direct mechanistic link between the changes associated with urban development and declines in stream biological condition. These measures provide a more sensitive understanding of stream-basin response to urban development than does treatment of each increment of impervious area equally. Land use in residential backyards adjacent to streams also heavily influences stream condition. Successful stream rehabilitation thus requires coordinated diagnosis of the causes of degradation and integrative management to treat the range of ecological stressors within each urban area, and it depends on remedies appropriate at scales from backyards to regional stormwater systems.

Key terms: aquatic ecosystems, flow, IBI, homeowner behavior, residential conditions, stream rehabilitation, urban water management.

## INTRODUCTION

The movement of people from farms to cities began thousands of years ago, accelerated in the twentieth century, and continues into the twenty-first century. By one estimate, 83% of people in Europe and the Americas will live in cities by 2025 (Sheehan, 2001). Urbanization

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alters river ecology in and downstream of cities, harming aquatic systems and prompting efforts to protect, rehabilitate, and even fully restore urban streams. Yet these efforts seldom succeed, mostly because of narrowly prescriptive solutions that do not take advantage of interdisciplinary knowledge in the physical, biological, and social sciences or because they do not treat the full range of urban change in streams (Karr and Rossano, 2001).

In the Pacific Northwest, where continued decline and now Endangered Species Act listings of the region's salmonids fuel public and government agency interest in watershed management, such interdisciplinary efforts are long overdue. Major expenditures are expected over the next decade in the name of "stream enhancement" and purported salmon restoration. Historically, similar expenditures have gone toward narrow fixes of single perceived problems, such as urban runoff, or toward treating symptoms, such as absence of woody debris in streams, rather than root causes, such as alterations in hydrology, riparian vegetation, and human attitudes and behavior. Too often, imperfect analyses combine with conflicting socioeconomic interests and politics to limit rehabilitation success. Yet the region needs integrative and diagnostic approaches to maintain its quality of life for people and stream biota. This report describes work that integrates channel hydrology, river biology, and human activity at diverse spatial scales to improve the condition of urban streams.

This study sets up a conceptual framework for assessing stream degradation and uses it to recommend realistic improvements. Few urban streams can be entirely restored—that is, returned to a state that supports the full range of living things and ecological processes characteristic of the least-disturbed streams of similar size and slope in a region. Many urban streams can, however, be *rehabilitated*—that is, their biological condition (state or health) can be improved to some degree. The framework used here explicitly links the human actions collectively termed "urbanization" with biological condition, the primary endpoint of concern (Figure 1). Urbanization does not itself cause biological decline; instead, it alters the landscape, inflicting stresses on stream biota. Successful stream rehabilitation requires understanding the many stressors and their interactions, which link human actions to biotic changes (e.g., Grimm et al., 2000). This complexity demonstrates the futility of one-size-fits-all urban restoration.

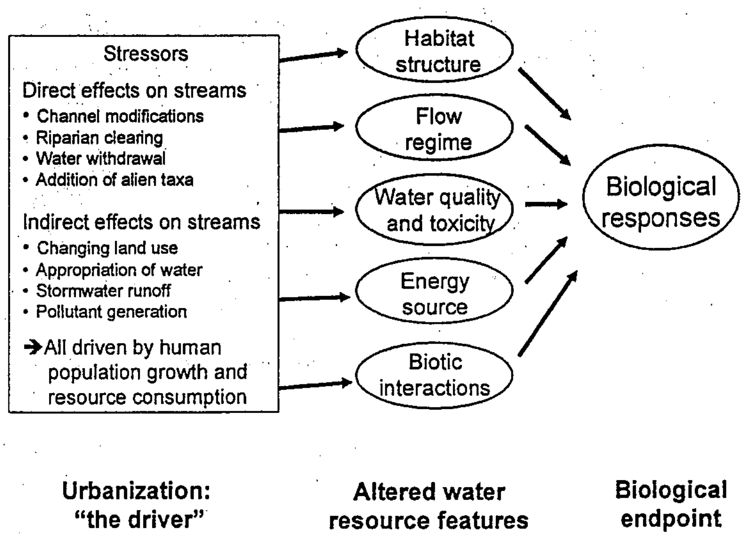


**Figure 1.** Conceptual model of the varied stressors resulting from human actions that alter stream biological condition. (Modified from Karr and Yoder, 2004).

This study focuses on the effects of human actions at spatial scales ranging from backyards to urbanization of entire subbasins. The study emphasizes the effects of such actions on channel hydrology and, in turn, outcomes in the biological condition of urban streams. Development-induced flow alteration was neglected in recent decades, when water chemistry dominated water resource management. Recent studies in the Northwest, however, suggest little if any relationship between water quality parameters and biological health in lightly to moderately urbanized watersheds (May et al., 1997; Horner and May, 1999). Thus, the focus here is on other factors likely to display significant relationships.

## URBANIZATION IS NOT A SIMPLE PHENOMENON

Stream degradation caused by urbanization is not a single problem with a single solution, or even a well-defined set of problems with well-defined solutions. Rather, stream degradation results from a collection of individual decisions and actions that leads to specific urban landscapes and, in turn, to altered stream condition. "Urbanization" itself is multidimensional and has been defined in many different ways (McIntyre et al., 2000). It may constitute industrial, retail, or housing development; it may proceed quickly or gradually. It can be halted at an early stage by zoning or hastened by incentives that encourage development. An urbanized watershed may contain polluting or nonpolluting industries, dense road networks or only a few roads. The topography, soils, vegetation, and channel networks in an urban basin may be altered. Thus no single change defines urbanization; instead, the cumulative effect of the variety of human activities in urban basins profoundly influences urban streams and their biota (Figure 2). Because of this complexity, successful rehabilitation must combine knowledge of the biophysical processes and conditions that sustain a specific stream system with knowledge of the drivers of degradation in that system.

**Figure 2.** Juanita Creek in the Puget Sound lowlands, heavily influenced by intensive human land use throughout its watershed.

## STUDY REGION AND SITES

Streams within the Puget Sound lowlands of western Washington State share relatively uniform physical and biological environments, which allow direct comparisons among streams. For this study, 45 sites from 16 second- and third-order streams in King, Snohomish, and Kitsap Counties (Figure 3) were selected with the following characteristics: watershed area between 5 and 69 $km^2$; local channel gradients between 0.4 and 3.2 percent; climate, elevation, and soils typical of the central Puget Sound lowlands; historical presence of anadromous salmonids; and urban development as the dominant human activity. Selected sites matched these factors but varied in level of urbanization from low-disturbance, or "reference," locales to intensively urbanized watersheds. Some watersheds still support regionally valuable biological resources, such as anadromous and resident salmonids or diverse invertebrate assemblages; others do not.

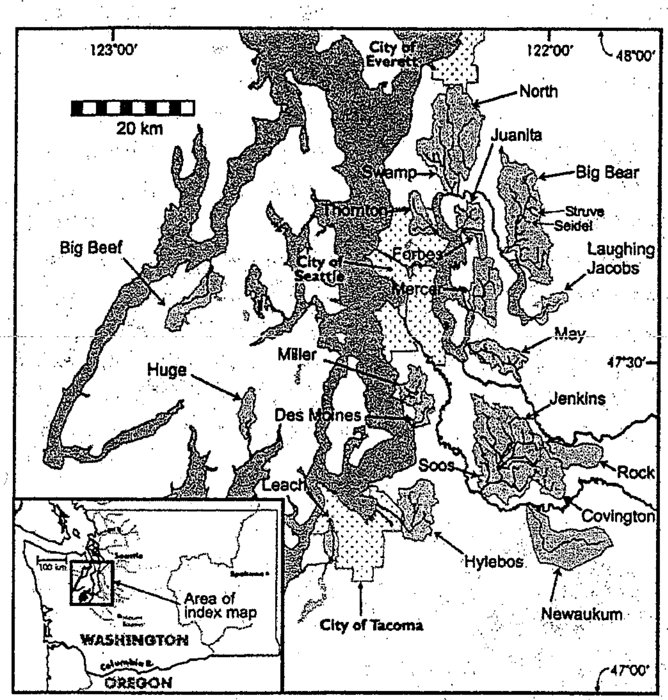


**Figure 3.** Puget Sound region with location of the study streams and watersheds. Area of major urban centers are stippled; study watersheds are shaded.

## STUDY DESIGN AND METHODS

The nature, and the causes, of change to aquatic system health were explored along a gradient of human activity (the primary independent variable), characterizing intensity of "human activity" with two common measures of land cover: urban land cover and total impervious area. Both characterizations used a 1998 Landsat image classified into seven land-cover categories at 30 m resolution, which included three "urban" classes (intense, grassy, and forested); three predominantly vegetated classes (grass/shrub, deciduous, and coniferous); and open water (Hill et al., 2003). Percentages for the three urban classes were summed to equal "urban land cover."

Total impervious area (TIA) is the fraction of a watershed covered by built surfaces or bare ground, such as unpaved roads or trails, that are presumed not to soak up water. On the basis of airphoto interpretation of representative areas across the study area, individual TIA factors were determined for each of the seven land-cover classes (Hill et al., 2003). For six sites that lacked direct measurement, TIA was estimated from the correlation between road density and TIA from eight other study watersheds ($r = +0.96$, $p < 0.001$). Hydrologically this TIA definition is incomplete, because it ignores supposedly "pervious" surfaces that are compacted or otherwise so nearly impermeable that runoff rates from them are similar to or the same as those from pavement. In addition, it includes some paved surfaces that are small or isolated. Runoff from such areas may be absorbed by adjacent pervious surfaces and thus contribute nothing to the storm runoff response of the downstream channel. Nevertheless, this study follows the common practice of using TIA as a primary index of urbanization, recognizing that it is an imperfect measure of not only human disturbance but also the diverse hydrologic, chemical, physical, and biological stressors and their consequences that follow urban development.

The primary dependent variable is stream health, measured using the 10-metric benthic index of biological integrity (B-IBI; Karr, 1998). B-IBI includes measures of taxa richness, tolerance of disturbance, dominance, and characteristics of selected ecological groups (e.g., clingers, predators). From 1995 to 1999, benthic invertebrates were collected during September, when flows are typically stable, taxa richness is high, and sites are easy to get to (Morley and Karr, 2002; 1995 data from J. R. Karr, unpublished). At each site, a Surber sampler (500 µm mesh) was used to collect three replicate 0.1 $m^2$ samples along the midline of a single riffle. Samples were preserved in the field and identified in the lab, generally to genus, without subsampling (as recommended by Karr and Chu, 1999). Sites with biological conditions at or near the condition of minimally influenced "reference" streams were given a score of 5, while moderately or severely degraded streams were scored 3 and 1, respectively. Scores for each of the 10 metrics are summed to yield site B-IBIs ranging from 10 to 50, divided into descriptive classes of excellent (46–50), good (38–44), fair (28–36), poor (18–26), and very poor (10–16). The B-IBI for each site provides a robust and convenient way to explore the relationships between land cover and overall biological condition.

The relationship between human influence (urban land cover) and biological condition (B-IBI) were examined at three spatial scales for each sample site: ***subbasin*** (i.e., the entire watershed upstream of the sample site); ***riparian*** (a 200-m-wide buffer on each side of the stream extending the full length of the upstream drainage network); and ***local*** (a 200-m-wide buffer on each side of the stream extending 1 km upstream (Morley and Karr, 2002).

Hydrologic consequences of urban development have long been documented for individual storms (Leopold, 1968; Hollis, 1975), but such consequences over longer periods are scarcely explored. Because longer term effects should be especially important to stream biota (e.g., Shelford and Eddy, 1929; Odum, 1956; Horwitz, 1978; Poff and Allan, 1995; Poff et al., 1997), two hydrologic metrics were developed to represent stormflow and baseflow patterns over multiple-year periods (Konrad and Booth, 2002): the fraction of a year that the daily mean discharge exceeds the annual mean discharge ($T_{Qmean}$); and the fraction of a multiple-year period that streamflow exceeds the discharge of the flood peak that occurs, on average, twice each year ($T_{0.5\,yr}$). Streamflow patterns were analyzed for water years 1988 to 2000 (water years begin on October 1) using records from 15 gaging stations within 5 km of B-IBI sampling sites and without large intervening tributaries (Table 1).

$T_{Qmean}$ measures daily streamflow through time relative to the mean discharge of a stream. The annual mean discharge ($Q_{mean}$), which is not strongly altered by urban development (Konrad and Booth, 2002), serves as a basis for normalizing streamflow patterns in comparisons among streams. The number of days when daily mean discharge ($Q_{daily}$) exceeded $Q_{mean}$ were calculated for each year of record for each stream. $T_{Qmean}$ was then calculated as the average annual fraction of a year that $Q_{daily}$ exceeded $Q_{mean}$ (commonly about 100 days per year for the streams in this study), which yields lower fractions for "flashy" streams and higher fractions for gradually varying flow regimes.

**Table 1.** Puget Sound lowland stream study sites.

| Stream | Site ID | Subbasin % TIA | Local % urban | $T_{Qmean}$ | $T_{0.5\,yr}$ | B-IBI |
|---|---|---|---|---|---|---|
| Big Beef | BB_1995 | 5 | | 0.28 | 0.009 | 26 |
| Rock | RO971/982 | 9 | 14 | 0.39 | 0.034 | 48 |
| Big Bear | BB974 | 15 | 37 | 0.33 | 0.011 | 34 |
| Covington | CV_1995 | 16 | | 0.37 | 0.054 | 42 |
| May | MA971 | 19 | 34 | 0.32 | 0.014 | 24 |
| Jenkins | JE971 | 21 | 56 | 0.42 | 0.020 | 32 |
| Big Soos | BS971 | 33 | 55 | 0.34 | 0.039 | 26 |
| North | NO982 | 35 | 44 | 0.30 | 0.005 | 22 |
| Hylebos | HY_1995 | 37 | | 0.32 | | 22 |
| Swamp | SW982 | 38 | 53 | 0.31 | 0.003 | 28 |
| Des Moines | DM_1995 | 39 | | 0.27 | 0.002 | 16 |
| Mercer | KE_1995 | 46 | | 0.26 | 0.003 | 12 |
| Thornton | TH98DS | 51 | 89 | 0.29 | 0.004 | 12 |
| Miller | MI971 | 54 | 45 | 0.26 | 0.002 | 12 |
| Juanita | JU_1995 | 59 | | 0.28 | | 10 |

$T_{0.5\,yr}$ is an equivalent measure of streamflow through time, but instead of using a common discharge ($Q_{mean}$ equaled or exceeded 1/3 of the time), this metric records the fraction of time that a stream channel is exposed to flows whose magnitude exceeds a more significant, less common flow. This metric also reflects the influence of urbanization on hydrology because high flows tend to increase in frequency, but not in duration, in response to urban development; that is, individual high-flow events occur more often with more development. A significant relationship between this hydrologic parameter and stream health was anticipated because field data show that frequent high flows continually destabilize channels rather than develop a new equilibrium form (Konrad et al., 2002). The 0.5-year flood, calculated from a partial-duration series of peak discharge (Langbein, 1949), was chosen as the discharge index because it has plausible geomorphic and biological significance: half-year floods occur often enough to exert persistent effects on stream biota (typically occurring about 100 *hours* per year in the sample set), and they transport streambed sediment in most alluvial channels (Pickup and Warner, 1976; Sidle, 1988). Values of $T_{0.5\,yr}$ were log-transformed before testing for correlations with impervious area and B-IBI.

In addition to hydrologic impacts, any integrative regional effort to rehabilitate urban streams must incorporate understanding of the behavior of individual landowners, because small lowland streams in western Washington pass predominantly through residential backyards, places where landscape decisions are often made without attention to community norms (Nassauer, 1993). Common metrics of watershed land use, flow regime, and biological condition (including ours) do not account for the effects of local landowners' decisions about streams on their property. This phase of the study was a prototype effort to fill a gap currently present in virtually all stream assessments in the Pacific Northwest and elsewhere. It emphasized individual behavior, not attitudes or opinions, because people often do not do as they think or say (Anderson, 1996).

The assessment of human behavior combined mailed questionnaires, interviews, and on-site visits (Schauman, 2000). The questionnaires were mailed to 520 streamside homes in three basins with a range of property values and urban density, but all adjacent to streams with active salmon runs and are extremely valuable habitat. Ninety-six (18%) completed surveys were returned. No follow-up measures were taken to increase the response level. Data were compiled using an analysis of means. Forty sites were photo surveyed to depict actual practices for comparison with preferences stated in the mailed questionnaires. The private properties ranged from those in watersheds having county-funded outreach programs, including a stream steward, to backyards in neighborhoods with little community awareness of their local streams.

## RESULTS

### *Changing Land Use Influences Biological Condition*

Biological condition as measured by B-IBI generally declined as urban development measured by TIA increased (Figure 4). TIA alone, however, cannot be used to predict biological condition at a given site. The upper limit of attained biological condition correlates well with the overall measure of urban development, displaying a "factor ceiling distribution" (Thomson et al., 1996) that defines the best biological condition associated with a given degree of watershed imperviousness (dashed line at upper edge of data in Figure 4). Yet degraded streams (low B-IBI) may occur at any level of watershed imperviousness; highly variable biological conditions were particularly evident at low to moderate development levels (see also Karr and Chu, 2000). As development intensity increased, the range of biological condition narrowed; in the most urban watersheds, conditions were uniformly poor. Across all study sites, B-IBI correlated significantly with urban land cover (i.e., the combination of "intense," "grassy," and "forested" urban categories) at the three spatial scales: ***subbasin*** ($r = -0.73, p < 0.001, n = 34$); ***riparian*** ($r = -0.75, p < 0.001, n = 34$); and ***local*** ($r = -0.71, p < 0.001, n = 31$) (Morley and, Karr 2002). Riparian and subbasin land cover was highly correlated ($r = +0.98, p < 0.001, n = 34$), but local and subbasin land cover was not.

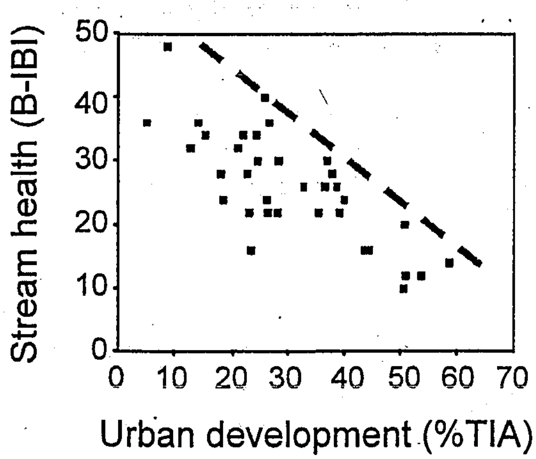


**Figure 4:** Stream health (measured using the benthic index of biological integrity, B-IBI) declines as subbasin urbanization (measured by total impervious area, TIA) increases. Plotted samples collected in 1997, 1998, and 1999.

Associations between urban development and stream condition have been explored for more than two decades. "Impervious area," commonly defined as the fraction of the contributing watershed that is paved or covered with buildings, is the most common metric used to capture development intensity. The earliest systematic study of the relationship (Klein, 1979) reported a rapid decline in biological diversity where watershed imperviousness exceeded 10 %. This observation gave rise to the expectation that keeping development below 10–15% TIA (a "threshold-of-effect") would protect stream health (see Klein, 1979; Booth and Reinelt, 1993; Schueler, 1994; Schueler and Holland, 2000; Paul and Meyer, 2001; Beach, 2002).

Other studies, however, point out that stream condition reflects a far more complex interplay of factors than a simple threshold of impervious surface can take into account (Steedman, 1988; Karr and Chu, 2000; Segura Sossa et al., 2003; Alberti et al., in press). For example, a wide range of stream conditions may be associated with low to moderate imperviousness, reflecting watershed sensitivity (as due to soils and surficial geology; Allan et al., 1997; Booth et al., 2003); the spatial patterning of impervious area and other modified land cover on the landscape (Steedman, 1988; Fore et al., 1996; Segura Sossa et al., 2003; Alberti et al., in press); and the effect of point sources of pollution and other human activities (Karr and Chu, 2000). Indeed, detailed work in the Pacific Northwest and elsewhere has often demonstrated substantial biological degradation at TIAs below 10% (May et al., 1997; Booth and Jackson, 1997; Karr, 1998; Horner and May, 1999; Karr and Chu, 2000; Booth et al., 2001), a fact that is now recognized by some prior proponents of the 10–15 % "threshold" (e.g., Center for Watershed Protection, 2003). Thus, although data from this and previous studies may support the use of TIA as a broad index of certain forms of human disturbance and perhaps as an upper bound on potential stream condition, they do not justify its use as a predictor of stream health or as a guide to "acceptable" thresholds of development.

*Hydrologic Change Imposes Basinwide Stress*

In selecting $T_{Qmean}$ and $T_{0.5\,yr}$ to explore the hydrologic effects of urban development, this study abandoned traditional emphasis on the damage caused by massive flooding on urban infrastructure such as roads, industrial parks, and homes. Two new metrics succeeded in capturing the hydrologic effects of urbanization, despite local variability in soils, geology, and watershed topography among Puget Sound lowland basins (Table 1). For example, $T_{Qmean}$ varied from 0.26 in Mercer Creek to 0.42 in Jenkins Creek; as TIA increased, both $T_{Qmean}$ ($r = -0.61, p = 0.008, n = 15$) and $T_{0.5\,yr}$ ($r = -0.72, p = 0.003, n = 13$) decreased significantly (Figure 5). Other influential factors (e.g., size, geology, topography of watershed) are likely responsible for some of the unexplained variation.

Stream biological condition also varied significantly with these streamflow metrics (Figure 6a, b); B-IBI is higher in less flashy watersheds (more stable flow regimes). Correlation coefficients were comparable for relationships between both streamflow metrics and biological condition, as well as between land cover and biological condition ($r = -0.84$, 0.82, and 0.80 for B-IBI vs. %TIA, $T_{Qmean}$, and $T_{0.5\,yr}$, respectively; $p < 0.001$ in all cases).

A major advantage of the flow attributes, however, is that they provide a more mechanistic basis—a more precise diagnosis—for understanding the causes of biological degradation (e.g., flashy discharges) beyond what is revealed from a simple correlation with TIA. For example, among nine streams with local urban land cover data available, all sites with local urban land cover of 54% or more fall below and to the right of the main trend (Figure 6c);

that is, the sites' biological condition was poorer than hydrologic conditions alone would have predicted. In contrast, sites with less local urban land cover (here, 14–53%) fall above and to the left of the main trend, meaning that biological condition was better than predicted by hydrology. No similar secondary patterns are discernible on a plot of TIA vs. B-IBI (e.g., Figure 4).

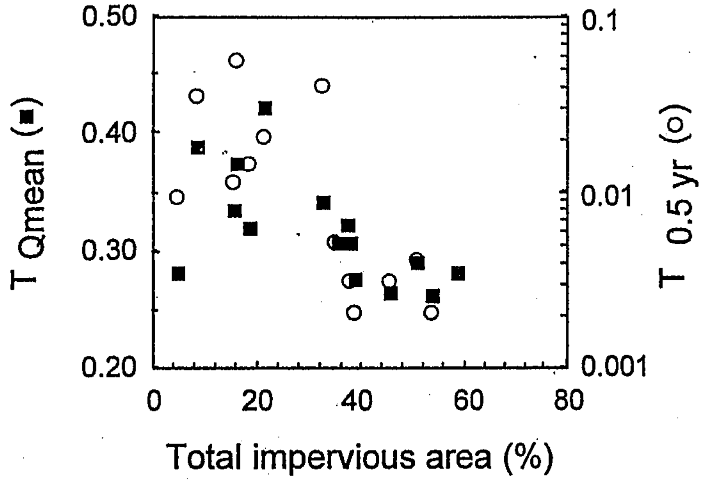


**Figure 5.** Discharge flashiness as measured by two hydrologic metrics ($T_{Qmean}$, left axis; $T_{0.5\,yr}$, right axis) (lower = flashier).

Available data do not allow us to identify a sole cause for these patterns. In some cases, variability is probably due to the influence of local land cover, but in others watershed hydrology may play the bigger role. For example, the Jenkins Creek site (JE971) had a "fair" B-IBI of 32 and an intermediate TIA (21%). This apparent correspondence masks one of the least flashy watersheds in the region ($T_{Qmean}$ = 0.42, highest in the study), where very high infiltration greatly reduces surface runoff despite a history of channel straightening and minimal riparian forest near the sampling site. These conditions are readily interpreted from the $T_{Qmean}$ vs. B-IBI relationship (see Figure 6) but are not at all evident from the plot of TIA vs. B-IBI (see Figure 4).

Even with ecologically appropriate measures of flow, however, one must remember that stream conditions are not determined solely by flow regime, which in turn is not determined solely by urban development. Intrinsic watershed characteristics—watershed geology, soil permeability and depth, topography, channel network, and climate—are also relevant (Booth et al., 2003). Thus no single watershed indicator should be expected to predict flow regime or all the consequences of changes in flow for stream conditions.

*Actions by Individuals Impose Local Stress*

The assessments of human behavior, specifically the actions of individual landowners, indicated substantial variation in backyard stream condition, reflecting an equally wide range of choices made by individuals in their private space. The private properties studied ranged from those adjacent to streams and located in watersheds having county-funded outreach programs, including a stream steward, to backyards in neighborhoods with little community awareness of their local streams. In all locations the range of conditions varied from benign neglect to severe, "ecopathic" alteration of private streamside property. Although no obvious simple explanation for these differences in behavior emerged, the behaviors nonetheless resulted in locally significant influences, whether benign or damaging, on stream health.

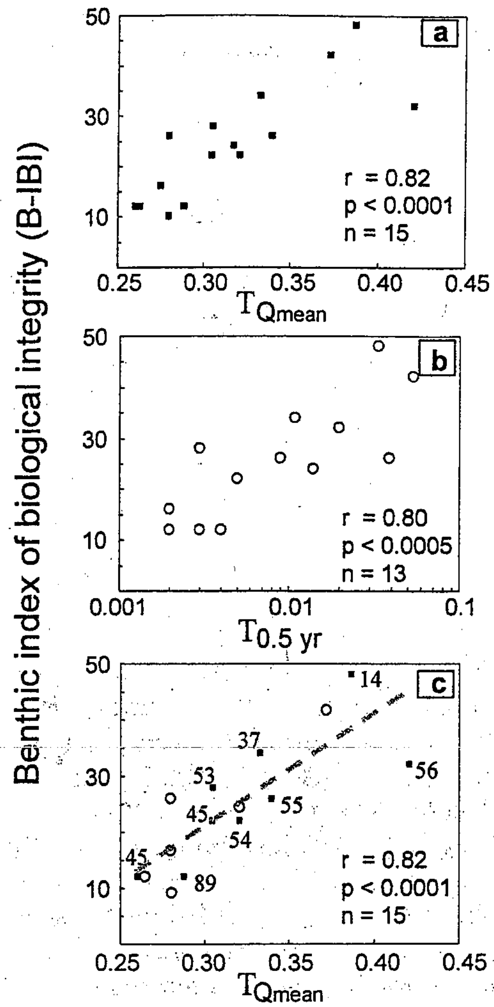


**Figure 6.** Relationship between benthic index of biological integrity and (a) $T_{Qmean}$ and (b) $T_{0.5\,yr}$. In (c), numbers indicate local urban land-cover percentage; sites plotted as circles lack local land-cover data.

Respondents were asked "What would most likely be your choice for three typical landscape design goals: Privacy and boundary design, individualistic design, or ecological care?" Of these three goals, "ecological care" was mentioned most often in the surveys, although the differences among the mean values for the different goals were not statistically significant. When asked on the mailed survey to specify the three "most important considerations in their landscaping or gardening," however, fewer than 10% of respondents indicated that any ecological considerations were important. The overwhelming response (>75%) to this question was "low maintenance." Many respondents repeated this desire three times: ease of maintenance dominated all other concerns.

Analysis of photos taken during site visits to the homes where "ecological care" rated as the highest goal showed some ecologically caring behaviors, such as composting, but no actions that could be described as streamside rehabilitation or restoration. The most prominent "ecological care" behavior was to comply with stream corridor buffer regulations in newer subdivisions on lots with a steep grade separating the backyard from the stream. No one planted buffers in older subdivisions, however, where trees had previously been cleared.

In 4 of the 40 photo-surveyed backyards, elaborate landscape designs included one or more artificial ponds reaching the high groundwater table adjacent to the stream (Figure 7). In another case the lawn stream edge was mowed for more than 60 m with two concrete vaults set into the bank, which the resident described as "salmon rearing boxes." Residents were proud that each year they raised silver salmon (*Oncorhynchus kisutch*) fry obtained at local hatcheries for release into the stream. They always had backyard gatherings and parties to watch sockeye salmon (*O. nerka*) spawn. Such residents place high value on their direct experience with fish.

**Figure 7.** Backyard stream. Rock banks, grass to stream edge, straightened channel, symmetrical plantings installed by streamside neighbors in the name of "stream enhancement."

In suburban sites older than 10 years, many backyards contained benches on lawns along the stream edge. In newer subdivisions where a riparian buffer was mostly intact, streamside benches had been placed at the end of a path leading through the buffer from the family's part of the backyard. These were often simple settings where one person might sit to contemplate nature. Clearly, people desire direct connection with their streams, but this desire did not always translate into positive acts. Given continuing, massive outreach and education efforts throughout the region, a few instances were anticipated where individuals would have planted buffers or attempted to revegetate the banks, yet none were found. Instead, banks were cleared along all streams.

Thus, individuals often do not take personal responsibility for rehabilitation on private property, even though many of the same residents may recognize "salmon habitat rehabilitation" as a worthwhile regional goal and take personal pleasure in its success. The factors responsible for this behavior are no doubt numerous and tangled, a mix of wanting maintenance ease along with enhancement of salmon populations and river health. The lack of clear guidelines on what to do and how to do it probably also plays a big role, however, as is clear at an institutional level from the efforts to release hatchery fish despite overwhelming evidence that doing so is unlikely to produce more salmon or healthier rivers (Lichatowich, 1999).

The importance of local stressors can also be demonstrated within a watershed context. Measured biological condition changed substantially along a section of Little Bear Creek (Figure 8), despite nearly identical subbasin TIAs for all sampling sites. Variations in riparian land cover in the 1-km upstream zone ("local") and even greater differences in conditions immediately adjacent to each sampling site, however, are strongly correlated to the variation in biological condition. The changes are evident in the area of Figure 8 and even more so in the watershed as a whole; for example, B-IBI was 40 at a site 5 km upstream of the pictured area, where more extensive riparian forest and wetlands remain. In the image, dark areas are forest or low-density residential areas; light areas are primarily industrial sites along a state highway that parallels the creek and exits the view in the upper right corner.

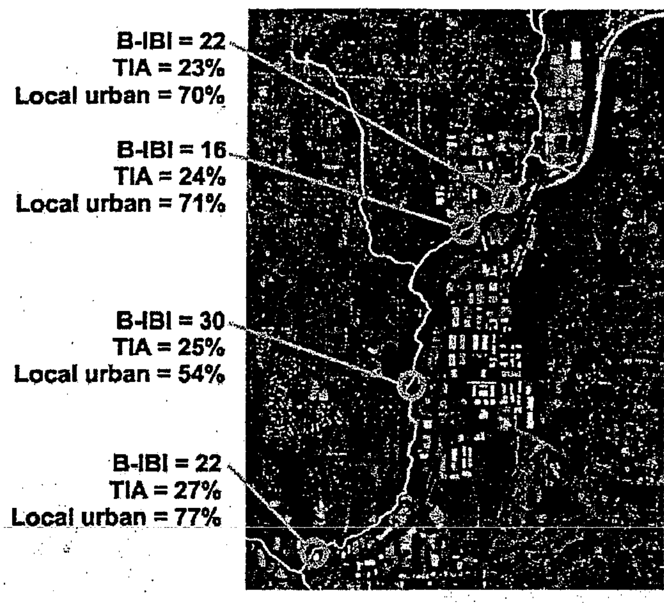


**Figure 8.** Variation in biological condition (B-IBI) along a section of Little Bear Creek near Woodinville, Washington, despite nearly identical subbasin TIAs at all sites. Pictured area covers 3.4 by 4.6 km.

## SYNTHESIS AND MANAGEMENT RECOMMENDATIONS

This research demonstrates that impervious area is not a reliable surrogate of biological condition, despite a pattern of broad biological decline with increased impervious area. Impervious area does provide a rough measure of the watershed area people have appropriated, and therefore it serves as a proxy of human influence. But as such, it cannot define the specific nature of human influences in a watershed or serve as a surrogate for biological condition. Direct biological measures are essential to infer stream health and to help diagnose the likely causes of degradation.

Important lessons for urban stream management emerge from the relationship between land use and biological condition. First, urbanization does not affect all streams the same way. The degree of urbanization and the specific complex of activities characterizing local development differ for each stream. The result is a lack of a precise association between stream health and urban development (Figure 9, left). Variation in biological condition is high at low levels of development but less variable as development increases (wedge shape). Second, any effort to manage a specific stream must relate stream biological condition to specific human activities and their effects in that watershed. Not doing so is akin to prescribing a cure for an ill person without identifying his symptoms or looking for their likely causes.

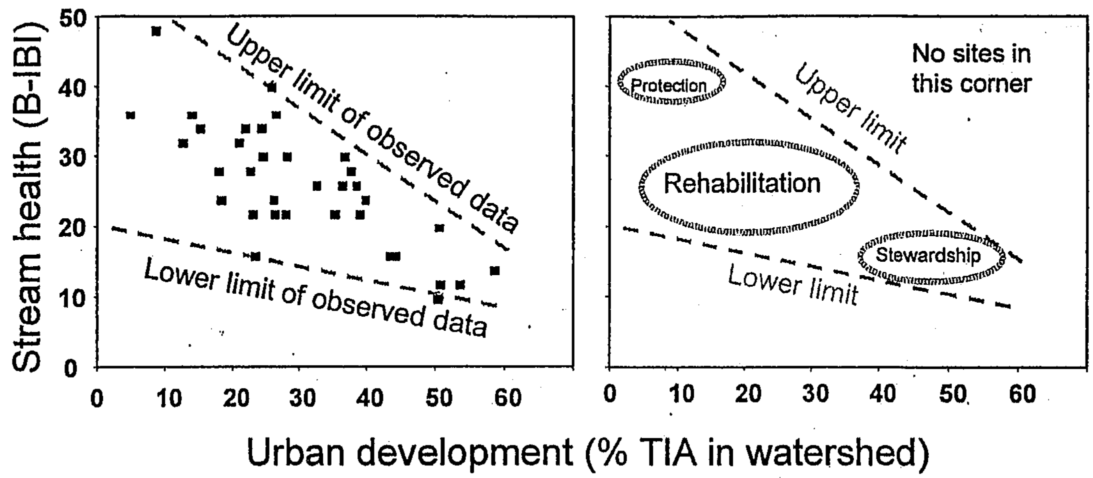


**Figure 9:** Left: Association between stream health (benthic index of biological integrity; B-IBI) and urban development (% total impervious area; TIA). Right: Recommended primary management strategies.

Although individual urban streams demand individual rehabilitation plans, some general guidelines apply (Figure 9, right). Streams or stream reaches in the upper left of the figure (labeled "Protection") support the richest biota and the highest biological condition, perhaps approaching biological integrity or the state of the least-disturbed comparable streams in the region. Such areas should be targeted for priority protection and long-term conservation. The best streams to protect can be chosen using any number of methods, including B-IBI, as long as the method relies explicitly on biology. In King County, Washington, for example, the 1993 "Waterways 2000" initiative identified high-quality stream reaches and watersheds so that available funding could go toward purchasing development rights or toward outright acquisition. First, a committee of scientists and citizens used existing information to select watersheds in the best biological condition at the time. They considered the number of salmon species; number of vertebrate species in the riparian forest; presence of other native fish, amphibians, or aquatic invertebrates in each watershed; plus the percentage of developed area, forest cover, or protected lands and the percentage of stream length with 90-m-wide adjacent forest. Within watersheds ranked highest under these criteria, they then evaluated areas for potential acquisition by a second set of reach-scale criteria, including riparian forest size; riparian forest structure (stand age, species distribution); connectivity to other habitats and features; local richness and abundance of aquatic species; and such geomorphic conditions as braided areas, confluences, flood channels, and sources of gravel and groundwater. Countywide, using the first set of criteria, six watersheds were identified having a combined area of more than 1200 $km^2$, and, using the second set, the county eventually acquired or otherwise permanently protected more than 8 $km^2$. One such protected place lies along Rock Creek (Figure 10), whose B-IBI was the highest (48) of all measured sites in the Puget Sound region even though it has a low but not the lowest subbasin total impervious area (TIA = 9%). However, it also has highly infiltrative watershed soils yielding a $T_{Qmean}$ of 0.39 (second-highest among the sites) and an already well-protected riparian corridor (local urban land cover = 14%, least-disturbed of the sites).

**Figure 10.** Rock Creek, with the highest benthic index of biological integrity (B-IBI = 48; maximum = 50) in the Puget Sound region.

Another portion of Figure 9b (labeled "Rehabilitation") includes sites whose biological condition is moderately to severely degraded despite only little to moderate watershed urbanization. Improving such streams may be possible, but only after identifying the specific factors responsible for degradation and treating their effects. Individual behavior is especially important in these lightly and moderately developed watersheds, because individuals' choices affect both localized stream reaches and the larger watershed, where political control over land use and stormwater regulation ultimately determines flows, pollutant loads, and channel and riparian condition. Where these effects are limited or easily treated, a stream might be restored close to minimally disturbed conditions. But in other cases, the best hope may consist only of small improvements. Careful evaluation is the only way to direct public resources toward streams where real improvements can be achieved, lest limited funds be spent on rehabilitation projects with worthy goals but no biological outcome (e.g., Larson et al., 2001).

The third major section in Figure 9b (labeled "Stewardship") encompasses places where urban development is virtually complete, and biological condition is at its worst. Such places are often subject to a number of the most harmful human effects, including hydrological and stream channel modifications and substantial pollutant and sediment loads. The results (and common sense) show that, regardless of locale, neither widespread riparian replanting nor extensive hydrologic rehabilitation is feasible, and efforts to do so are unlikely to much improve biological condition. For example, Figure 11 displays two contrasting streams where riparian conditions are vastly different but their influence is overwhelmed by watershed urbanization. The left panel of Figure 11 shows Thornton Creek in NE Seattle (subbasin TIA = 51%; local urban land cover = 89%; $T_{Qmean}$ = 0.29; B-IBI = 12, "very poor"); the right panel is Miller Creek (subbasin TIA =

54%; local urban land cover = 45%; $T_{Qmean}$ = 0.26; B-IBI = 12), which drains the western half of Seattle-Tacoma International Airport. Thus, measuring riparian condition alone is not adequate to gage stream health, and replanting riparian zones does not guarantee improved stream biota.

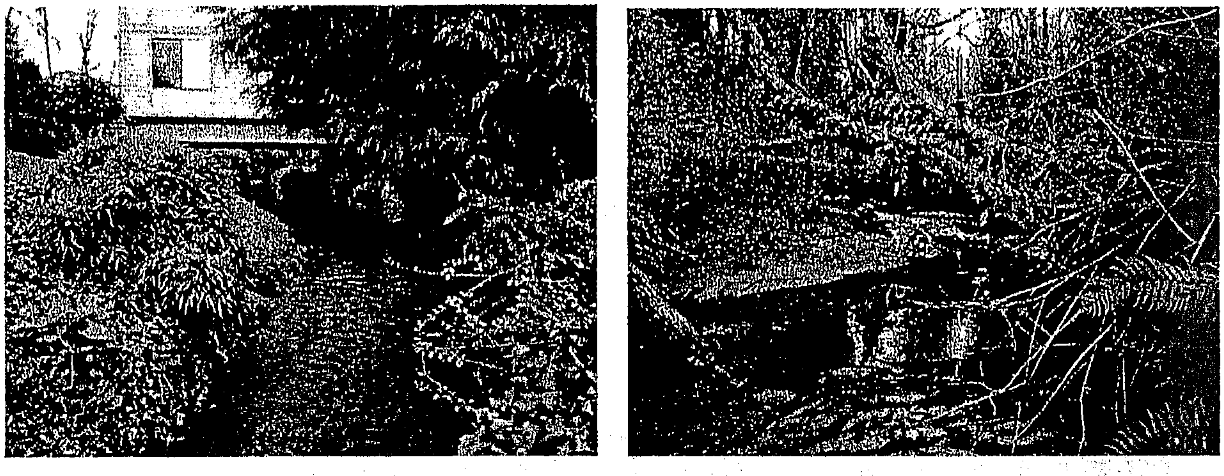

**Figure 11.** Contrasting riparian conditions in two highly urbanized watersheds. Left: Thornton Creek (B-IBI = 12, "very poor"). Right: Miller Creek (B-IBI = 12, also "very poor").

In such settings, the opportunity to protect such places has already been lost and full restoration is almost surely impossible. That said, however, people can "do no [further] harm" to such streams and can even improve conditions for both stream life and the people that live nearby. Neighborhood efforts—cleaning up, removing nonnative vegetation, replanting, even just leaving reaches alone—can improve local biological health, provide community amenities, and raise public support for regional enhancement efforts that may offer better hope for watershed-wide recovery (Groffman et al., 2003). Improvements in heavily degraded areas can also reduce downstream effects and help protect or rehabilitate downstream reaches.

In general, most urban streams flow through watersheds under significant human influence but where modest improvement is fully appropriate and achievable. Management programs, however, should rely neither on piecemeal application of structural best management practices (Booth and Jackson, 1997), nor on spot efforts to replace lost wildlife, for example by releasing hatchery fish that need whole healthy watersheds to survive. Such activities simply treat symptoms without dealing with the larger syndrome of diverse human influences.

Even for "modest" rehabilitation goals, therefore, as many of the following seven actions as possible are defensible and recommended:

1. Cluster development to protect most of the natural vegetative cover, especially in headwater areas and around streams and wetlands, so that riparian buffers remain intact (Booth et al., 2002; Morley and Karr, 2002).
2. Limit watershed imperviousness, either through minimal development or by reducing the "effective" impervious area through the widespread reinfiltration of stormwater (Konrad and Burges, 2001).
3. Mimic natural flow frequencies and durations, not just control peak discharges, when designing stormwater detention ponds (Konrad and Burges, 2001).

4. Protect riparian buffers and wetland zones, and minimize road and utility crossings (Morley and Karr, 2002; Meador and Goldstein, 2003; Alberti et al., in press).
5. Begin landowner stewardship programs that recognize the unique role of adjacent private property owners in rehabilitating, maintaining, or degrading stream health.
6. Apply knowledge from multiple disciplines—toxicology, hydrology, geology, biology, ecology, environmental design, public policy—and communicate that knowledge to all groups involved.
7. Stress the importance of measuring stream biota directly—along with physical, chemical, and landscape features—to diagnose causes of degradation, track the effectiveness of management programs, and connect regulations and incentives directly to both public preferences and legal mandates (Karr and Chu, 1999; Morley and Karr, 2002).

A major lesson of this analysis, then, is that fully restoring all developed and undeveloped watersheds is not feasible. This work has found no evidence that the impacts of urban development can be fully alleviated; in other words, there are no examples, in this or any other study, of sites that would fall into the upper right corner of Figure 9. People routinely underestimate the levels of mitigation needed to truly restore streams (Barker et al., 1991; Booth and Jackson, 1997; Jackson et al., 2001). Even if restoration were technically possible, people are unlikely to commit enough money or to commit to wholesale changes in land use in highly urbanized areas. Thus the key tasks facing watershed managers, and the public who can support or impede their efforts, are to identify watersheds where existing low urbanization and associated high-quality stream conditions warrant development strategies that protect the existing quality of these systems and to improve management of those watersheds where some rehabilitation is possible. In places where rehabilitation is likely to be successful, improving flow regimes and near-stream conditions are top priorities because of their demonstrated biological consequences.

Managing urban streams requires a blend of science, public policy, and individual actions (Karr, 2001). Society can no longer afford piecemeal fixes of only one driver of degradation (such as water quality, stormwater runoff, or land use planning); neither can society afford seemingly broad yet actually narrow goals (such as restoring salmon). Only by integrating what is known about stream locale, including landowner behavior; diagnoses of degradation's causes; and evaluations of biological condition can urban conservation or rehabilitation goals be accomplished. Success also will require agencies, institutions, and diverse stakeholder groups to coordinate their efforts (Wang 2001) and to go beyond a poorly articulated "balance" between ecological protection and social and economic costs (e.g., Pickett et al., 1997).

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# Urbanization and Streams: Studies of Hydrologic Impacts



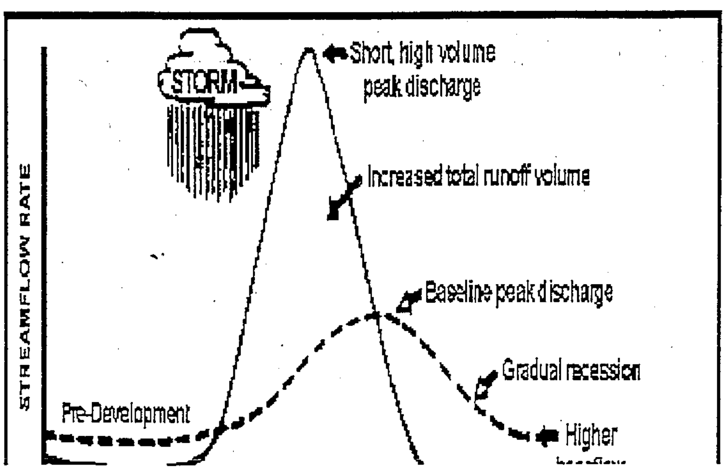
## Introduction

Hydrologic impacts due to urbanization are reported to cause water quality problems such as sedimentation, increased temperatures, habitat changes, and the loss of fish populations. Although there is widespread recognition that these problems are caused by increased runoff volumes and velocities from urbanization and associated increases in watershed imperviousness, much of the reported information has been anecdotal. The summaries and analyses of reports and case studies in this report are intended to go beyond the anecdotal and provide documentation of problems and sources, as well as a foundation for further investigation.

Planners, engineers, water quality specialists, and government officials should find this study a useful introduction to understanding the potential hydrologic impacts of urbanization on streams.

This report was derived from a literature search to find and document physical impacts and indications of water quality problems. United States Geological Survey reports; American Water Resources Association publications; federal, state, and local agency reports; journal articles; conference proceedings; and consultations with experts provided the documentation and case study examples cited in this report.

## Findings and Analysis




Examination of published literature revealed a large amount of anecdotal information that identifies hydrologic impacts on streams caused by increased impervious area (e.g., roads, driveways, parking lots, and rooftops) in urban developments. Figure 1 graphically depicts the impacts of urbanization on stream flow documented in the literature, and Table 1 summarizes the relationship between these changes in flow and other impacts in receiving streams. These impacts include increased frequency of flooding and peak flow volumes, increased sediment loadings, loss of aquatic/riparian habitat, changes in stream physical characteristics (channel width and depth), decreased base flow, and increased stream temperature.(1)

*1. For more information on impacts on streams due to urbanization, refer to the following: Fundamentals of Urban Runoff Management (Horner et al., 1994), Site Planning for Urban Stream Protection (Schueler, 1995), Effects of Urbanization on Aquatic Resources (Klein, no date), Environmental Indicators to Assess Control Programs and Practices (Claytor and Brown, 1996), Clearing and Grading Strategies for Urban Watersheds (Corish, 1995), and several articles in Watershed Protection Techniques (Center for Watershed Protection).*

**Table 1. Impacts from Increases in Impervious Surfaces.**

| Increased Imperviousness leads to: | Resulting Impacts | | | | |
|---|---|---|---|---|---|
| | Flooding | Habitat loss (e.g., inadequate substrate, loss of riparian areas, etc.) | Erosion | Channel widening | Streambed alteration |
| Increased volume | * | * | * | * | * |
| Increased peak flow | * | * | * | * | * |
| Increased peak flow duration | * | * | * | * | * |
| Increased stream temperature | | * | | | |
| Decreased base flow | | * | | | |
| Changes in sediment loadings | * | * | * | * | * |

Nine case studies that contained quantitative documentation linking urbanization to hydrologic impacts on streams were identified. They are summarized in Table 2 and are described in the appendix in more detail. It should be noted that some of the impacts identified in Table 2 are inferred from the presence of other indicators. For example, the Valley Stream, Pines Brook, and Bellmore and Massapequa creeks case studies from Long Island, New York, revealed a significant decrease in stream base flow resulting from increased urbanization within the contributing watersheds. Although habitat loss, average stream temperatures, and low dissolved oxygen concentrations were not reported in the study, these impacts typically occur as a result of decreased base flow and can be assumed (Horner et al., 1994; Klein, no date).

**Table 2. Results of Case Study Reviews**

| Case Study | Location | Documented Impacts | Inferred Impacts |
|---|---|---|---|
| Pheasant Branch Basin | Middleton, WI | • Stream incision<br>• Increase in bankfull events<br>• Sedimentation | • Flooding<br>• Habitat loss<br>• Erosion<br>• Channel widening<br>• Streambed alteration |
| Holmes Run Watershed | Fairfax, VA | • Frequent flooding<br>• Severe stream bank erosion<br>• Sedimentation | • Flooding<br>• Habitat loss<br>• Erosion<br>• Channel widening<br>• Streambed alteration |
| Peachtree Creek | Atlanta, GA | • Increased bankfull events<br>• Decreased base flow | • Flooding<br>• Habitat loss<br>• Erosion<br>• Channel widening<br>• Streambed alteration |
| Pipers Creek | Seattle, WA | • Increased peak flows<br>• Loss of fish populations<br>• Aesthetic degradation | • Flooding<br>• Habitat loss<br>• Erosion<br>• Channel widening<br>• Streambed alteration |
| Valley Stream, Pines Brook, Bellmore Creek, and Massapequa Creek | Nassau County, NY | • Decreased base flow | • Habitat loss |
| East Meadow Brook | Nassau | • Increased peak flows | • Flooding |

| | | | |
|---|---|---|---|
| | County, NY | | • Habitat loss<br>• Erosion<br>• Channel widening<br>• Streambed alteration |
| Kelsey Creek | Bellvue, WA | • Degradation of designated uses<br>• Decreased base flow<br>• Loss of fish populations | • Habitat loss<br>• Channel widening |
| Several Creeks | Dekalb County, GA | • Stream enlargement<br>• Stream incision<br>• Increased sediment transport | • Habitat loss<br>• Erosion<br>• Channel widening<br>• Streambed alteration |
| Patuxent River System | Maryland | • Increased instream sediment load<br>• Changes in morphology of urban channels | • Habitat loss<br>• Erosion<br>• Channel widening |

## Conclusions

There are documented case studies that conclusively link urbanization and increased watershed imperviousness to hydrologic impacts on streams. Existing reports and case studies provide strong evidence that urbanization negatively affects streams and results in water quality problems such as loss of habitat, increased temperatures, sedimentation, and loss of fish populations.

However, relatively few case studies have assembled detailed quantitative information to document these phenomena. This is due, in part, to (1) the heavy reliance on engineered approaches to runoff management that can transfer hydrologic impacts (e.g., habitat loss, flooding, channel widening, and erosion) to downstream areas through the construction of paved channels, stormwater pipes, and bank stabilization (e.g., riprap, cutbacks, plantings, bulkheads) and (2) the difficulty and high costs associated with long-term watershed monitoring. Furthermore, the installation of drainage structures, such as pipes and concrete channels, is the final step in removing urban streams from the landscape. Classically, many of these activities have resulted in urban streams being "written off" as virtually nonexistent; therefore, the resulting impacts on water quality and habitats are being ignored.

It is anticipated that in the future the literature will be supplemented with additional studies that document the relationship between urbanization, impervious surfaces, and problems in streams. Future investigations might include Federal Emergency Management Agency (FEMA) floodplain management activities. FEMA trend analysis of widespread changes in 100-year floodplain delineations or increased claims for financial assistance in specific watersheds might add increased evidence of hydrologic impacts due to urbanization. In the meantime, it is hoped that existing information proves sufficient to allow planners, engineers, and local officials to recognize potential hydrologic impacts due to urbanization and to take steps to prevent water quality problems while allowing for sensible development.

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# River Channel Change with Time: An Example

**Address as Retiring President of The Geological Society of America, Minneapolis, Minnesota, November 1972**


## ABSTRACT

Monumented channel cross sections were resurveyed over a period of 20 yrs (1953 to 1972) to determine the amount and kind of change of channel area and position on a 3.7-sq-mi basin, Watts Branch near Rockville, Maryland. For the first 12 yrs, the channel progressively but slowly became smaller as urbanization of the basin gradually proceeded. After 1966, a threshold of change apparently was passed and, probably as a result of an increased rate of land alteration upstream, large amounts of sediment were deposited within the channel and overbank. The number of floods exceeding channel capacity increased dramatically from an average of two to more than ten per year. Simultaneously, the channel area began to increase. Despite the trend toward increasing cross-sectional area, the net result after 20 yrs was a channel smaller by 20 percent than it had been originally. Urbanization did not alter the rate of channel migration.


## GENERAL STATEMENT

When one observes the many and great changes that have occurred in some landscapes since the beginning of the Pleistocene, he is inclined to the belief that a longer period of time was involved than he had been led to believe. Death Valley is an example where lakes of great depth once existed in a locality that is now a true desert. Segments of giant fans, some faulted, have been built out on the dried-up lake basin. Some large boulders on the fan surface are so deeply weathered that a hammer blow will reduce them to grus.

We are rapidly learning that certain geomorphic processes are much more rapid than we have been wont to believe. But only recently have geologists attempted to determine by actual measurement process rates formerly the subject of general reasoning or speculation. Such measurement programs have documented the fact that rates of landscape change are greater than had earlier been suspected.

This address is the result of a modest scheme I began two decades ago, in order to observe changes in the channel of a small river, thinking at the outset that the results might become of interest to the generation of my grandchildren, but not to my colleagues. I soon found, however, that the changes being observed occurred far more rapidly than I had expected, and the healing, the hiding, or the obscuration of such changes was much more complete and misleading than I had supposed. The present report

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presents the results of consecutive, repetitive measurement of channel change in a small river in a humid-temperate climate, and some thoughts on the need for more such observations.

## OBSERVATION PROGRAM

The river is Watts Branch, a small tributary of the Potomac River, north of Washington, D.C., arising in the rolling topography of the Piedmont which receives an annual precipitation of 44 in. The place of observation is where the small perennial stream meanders in a flat-floored valley. The drainage area is 3.7 sq mi. The purpose of the observational program was to describe the process and rate of lateral migration of the channel, the construction of point bars and flood plain, and the effects of meander curves on the process and rate. That part of the observational program discussed here consisted of 14 monumented cross sections which have been surveyed about every other year for 20 yrs, 1953 through 1972, inclusive. Much was learned on the subjects mentioned as the original purposes, but unexpectedly, the program has yielded some quantitative data on the effects of progressive urbanization in a small river basin.

An outline and location map of the basin is included in Figure 1. Figure 2 presents planimetric maps for 1953, 1959, and 1972, and shows the reach of the stream where the cross sections were established. As can be seen, the sections were located to represent a variety of positions relative to the meander curves and straight reaches of the river. Each cross section was monumented at both ends by ½-in. steel rods or pins usually 2½ ft long driven into the ground so that initially the top was a few inches below the surface. Though this made the rods less easy to relocate, they were not subject to disturbance either by vandals or by the mowing machine which, during the first few years, was used to cut the hay on the valley flat. A few bench marks were also established, usually a large nail or lag screw near the base of a tree. Distances from bench marks to some pins and between pins were measured with tapes. The triangulation network of distances was used to go progressively from exposed bench marks to individual pins and thence from located pins to those still hidden. Two tapes were held at known points and the intersection at recorded distances was the location of an as yet uncovered pin. At that location, a shovel was sliced beneath the sod in attempts to find the subsurface steel.

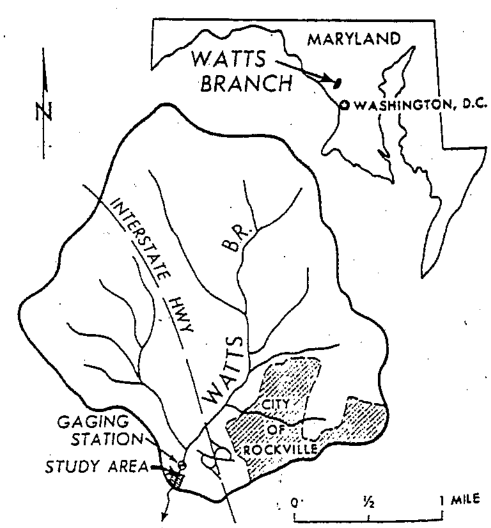

Figure 1. Planimetric and location maps of the basin of Watts Branch near Rockville, Maryland, above the study reach.

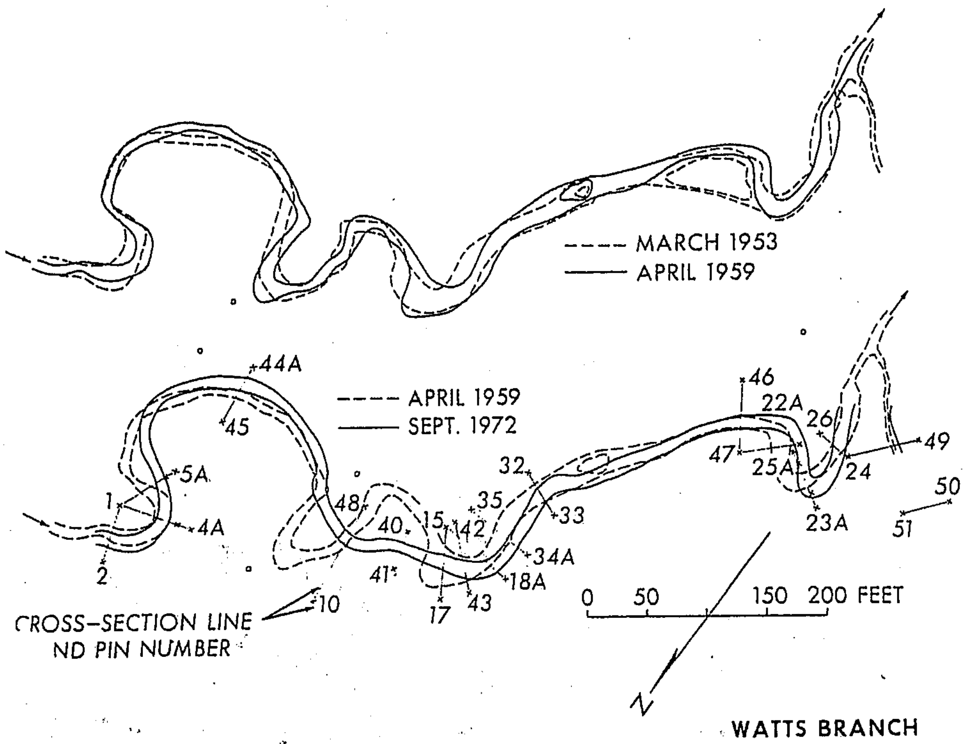


**Figure 2.** Planimetric maps of the study reach of Watts Branch for successive surveys. Upper, channel configuration in 1953 (dashed line) and 1959 (solid line); lower, 1959 (dashed line), and 1972 (full line) with location of cross sections.

For the first few years, the task of locating the pins was simple. The pastured field was a greensward of grass, and the pins lay only a few inches below the sod. In later years, the farm was sold, stock was removed, brush and weeds became rampant, and silt resulting from upstream development was deposited in quantity. Thus the digging required to find each pin became quite onerous.

Lateral migration of the river eventually exposed and then destroyed certain pins. Usually the cross section was preserved by establishment of a new pin on the same line. As the threat of urbanization became apparent, some new cross sections were added, especially across a small tributary where housing development was likely. This accounts for the fact that some cross sections were established later than others, and have a shorter record.

Because of this research program, I had established a U.S. Geological Survey stream-gaging station on Watts Branch, a few hundred feet upstream of the measurement reach. Thus flow records are available for most of the period of channel observation.

## CHARACTERISTICS OF VALLEY AND STREAM

In the study area on the Vier's farm, 900 ft downstream of Maryland Highway 28, valley floor is nearly flat and is 250 ft wide. The channel is about 25 ft wide at the ..., and this is the width of the flow at bankfull stage. At normal low water, the channel is about 12 ft wide. The channel banks are 2 to 4 ft high, and the depth of water at low flow is about 0.5 ft. The mean annual discharge is 3.2 cu ft per second (cfs); and at a straight and natural section, the bankfull discharge was 220 cfs before the effect of urbanization. Since that time, the average channel capacity at bankfull has been somewhat reduced, as will be explained. The gradient through the study reach is 0.0081. The bed alternates in elevation through a series of pools and riffles and is generally composed of gravel having a median size of 16 mm.

Bedrock underlying the valley floor is Wissahickon Schist, the surface of which lies only 6 to 7 ft below the surface and is remarkably flat. In places, gravelly regolith a few feet thick lies on fresh schist, but generally the bedrock is overlain by a foot of gray or mottled coarse gravel which, in turn, is covered with 5 ft of silt or clayey silt. The lower foot of the silt exposed in stream banks is gray, appears clayey in texture, and owing to the reducing environment below the water table, resembles a gley soil. The topography of the bedrock surface was exposed in a trench cut in 1961 for a sanitary sewer down the length of the valley. The design engineers must have sought no geologic information, for the sewer trench was blasted 6 to 7 ft into the bedrock for the full length of the line.

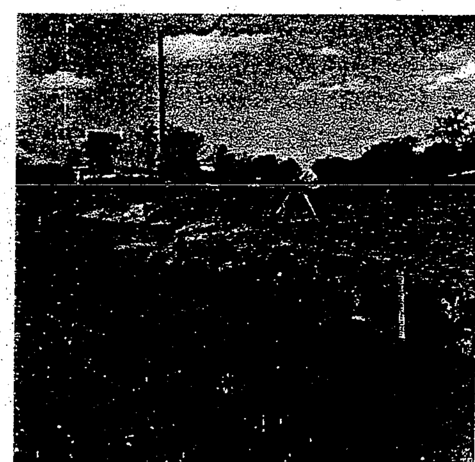

**Figure 3. Watts Branch in May 1953, looking upstream toward area where cross sections were established. Staff gage at natural section in right foreground and where bankfull stage was determined.**

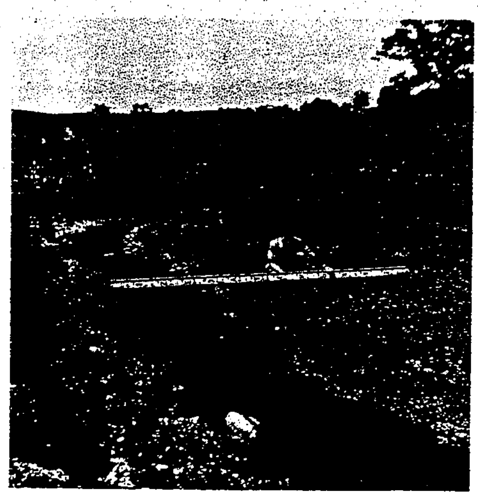

Figure 4. View downstream in 1959 at section 44A–45 for comparison with Figure 5.

Figure 5. 1971 view of same reach shown in Figure 4. Note greater prominence of blocks of sod falling off left bank. Also growth of willow brush on point bar to right.

Construction of the sewer trench destroyed some of the pins of the original cross sections and necessitated re-establishment of sections in unaltered portions of the reach, thus shortening the repetitive record significantly. The construction also cut off a meander bend between sections 44A–45 and 15–17, shortening the channel length by 130 ft.

The photographs of Figures 3 through 9 show the character of the stream and valley and the visual changes that occurred. Note especially the houses appearing in the background of the later pictures.

## PROCESS AND RATE OF CHANNEL MIGRATION

The successive maps (Fig. 2) show that channel movement occurs more or less at all places, greater on the curves than in straight reaches. In two decades, there were several

Figure 6. Downvalley view near section 1–2 in 1953. Compare with Figure 7.

Figure 7. 1971 view near section 1–2. Note flood debris in left foreground, and willow brush. New housing under construction in background.

Figure 8. Closeup of retreating bank near section 4[illegible]5 in 1971. Iron pin originally set well away from [illegible]as been exposed by bank retreat and is now bent ov[illegible] into channel. Sod lumps undercut by bank retreat fall into channel.

Figure 9. Stream bank which had been subject to ice crystal growth and loosening of surface layer. A moderate stream rise has removed this prepared material in lower third of the bank leaving a fresh surface of silt and showing the main mechanism of bank retreat.

places where the lateral migration amounted to more than the width of the channel.

The process by which this motion takes place is twofold, one erosional and one depositional. The erosion of a bank is not the result of erosion by high-velocity water, whether in a concave bank on a curve or in a straight section. Rather, for effective erosion to occur, the material must be loosened—which in this stream, is done by formation of ice crystals in winter. Crystals push soil particles out from a vertical bank of silt. When the ice crystals melt, usually on the day following formation, the grains of silt which cling to the points of growing crystals drop vertically and accumulate as a loosely structured debris cone at the base of the vertical bank. This process has been documented by Wolman (1959). The major floods occur in summer as a result of thunderstorm rain and are not effective in lateral erosion. Small rises in flow, separated by periods of freeze and thaw, are effective agents in channel migration. Details of point bar stratigraphy and its development from small increments of deposited sediments on point bars have been previously published (Leopold and others, 1964, p. 324–326).

## CHANGES IN CHANNEL CROSS SECTION

Point bar growth into the channel for the first decade kept pace with recession of the opposite bank, maintaining approximately the same channel width. However, the increase in sediment load associated with urbanization in the later part of the record resulted in building of higher banks, the channel cross section becoming less trapezoidal and more rectangular. This has caused a narrowing of the top width of the channel. This can be seen in the net changes of channel dimensions presented in Table 1. For each channel cross section, the dimensions are given at the time of first survey and in 1972. In interpreting the data in the table, it must be emphasized that there is considerable latitude in choice of the bankfull level of a given cross section, and the choice of this level determines all dimensions except mean bed elevation.

The cross sections presented in Figure 10 were chosen from the 14 available to represent

TABLE 1. CHANNEL OF WATTS BRANCH: DIMENSIONS AND ELEVATIONS AT TIME OF FIRST SURVEY AND IN 1972*

| Section | Year established | Bed elevation (ft) | | Change in bed elevation (ft) | Channel width (ft) | | Channel depth (ft) | | Bank elevation (ft) | | Change in bank elevation (ft) | Channel cross-sectional area (ft) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | original | 1972 | | original | 1972 | original | 1972 | original | 1972 | | original | 1972 |
| 1-2 | 1953 | 105.3 | 105.4 | +0.1 | 17.0 | 19.4 | 2.7 | 4.5 | 108.0 | 109.9 | +1.9 | 44.5 | 76.6 |
| 1-4 | 1953 | 104.0 | 105.5 | +1.5 | 27.4 | 19.5 | 5.0 | 4.3 | 109.0 | 109.8 | +0.8 | 94.4 | 69.0 |
| 1-5 | 1953 | 106.4 | 105.4 | -1.0 | 20.3 | 19.8 | 2.2 | 3.9 | 108.6 | 109.3 | +0.7 | 41.6 | 54.0 |
| 44A-45 | 1961 | 105.3 | 105.3 | 0 | 25.5 | 19.6 | 2.2 | 4.7 | 107.5 | 108.5 | +1.0 | 30.4 | 48.2 |
| 48-10 | 1962 | 103.7 | 104.0 | +0.3 | 17.7 | 21.9 | 2.1 | 3.7 | 105.8 | 107.7 | +1.9 | 20.5 | 51.0 |
| 40-41 | 1962 | 103.8 | 103.6 | -0.2 | 16.0 | 13.6 | 2.2 | 3.4 | 106.0 | 107.0 | +1.0 | 31.7 | 38.0 |
| 15-17 | 1953 | 101.5 | 102.9 | +1.4 | 35.2 | 23.1 | 4.5 | 3.6 | 106.0 | 106.5 | +0.5 | 133.0 | 59.5 |
| 42-43 | 1962 | 103.0 | 104.3 | +1.3 | 55.1 | 23.3 | 3.0 | 3.1 | 106.0 | 107.4 | +1.4 | 100.0 | 67.4 |
| 15-18A | 1953 | 103.0 | 103.5 | +0.5 | 33.4 | 17.1 | 3.3 | 4.2 | 106.3 | 107.2 | +1.2 | 85.0 | 50.5 |
| 33-34A | 1958 | 103.0 | 103.3 | +0.3 | 37.8 | 22.4 | 3.5 | 3.4 | 106.5 | 106.7 | +0.2 | 88.1 | 55.0 |
| 32-33 | 1956 | 102.9 | 103.0 | +0.1 | 25.5 | 19.6 | 3.1 | 4.0 | 106.0 | 107.0 | +1.0 | 52.1 | 63.9 |
| 46-47 | 1961 | 102.5 | 102.5 | 0 | 34.7 | 13.6 | 2.9 | 3.7 | 105.4 | 106.2 | +0.8 | 50.1 | 43.4 |
| 22A-47 | 1953 | 102.1 | 102.5 | +0.4 | 47.9 | 22.5 | 2.3 | 3.4 | 104.4 | 105.9 | +1.5 | 55.7 | .. |
| 26-24 | 1953 | 101.4 | 102.4 | +1.0 | 30.3 | 17.5 | 3.1 | 2.5 | 104.5 | 104.9 | +0.4 | 58.2 | 37.0 |
| Averages | | | | | 30.2 | 19.5 | 3.0 | 3.7 | | | | 63.2 | 55.0 |
| Averages for 20-yr record only | | | | | 30.1 | 19.8 | 3.3 | 3.8 | | | | 73.2 | 58.0 |

* *Elevations refer to an arbitrary datum.*

two types of change. Section 44A–45 is on a long gentle curve and shows considerable migration toward the concave bank. Section 1–2 is at the end of a straight reach just upstream of a meander curve. Little lateral migration occurred there. Location of these sections relative to the plan of the study reach can be seen on Figure 2.

In 1953 on the left bank of section 1–2, there was a distinct level or berm at elevation 108. In designating the level of top of channel or bankfull, I followed the general rule that the lowest extensive flat area or definite berm on either bank would be designated. Thus, in section 1–2, the elevation of bankfull stage was in 1953, 108.0; in 1966, 108.4; and 1972, 109.9. In making the choice of top of channel, several successive cross sections were inspected simultaneously and the choices attempted to maintain a continuity in the observed changes through the whole record.

Looking first at the net changes from date of establishment to 1972 for all cross sections, Table 1 shows that the average area of channel decreased 13 percent and for only those sections having the full 20 yrs of data, 21 percent. Channel depth increased one-half foot, but this was due to an increase in the height of the banks, not to deepening of the bed. Without exception, all sections showed an increase in elevation of river banks (Table 1, col. 12). Mean bed elevation rose slightly at 10 of the 14 sections. Because width at top of hannel decreased by about one-third, it can be seen that the sections became more rectangular, smaller, deeper, and narrower. The sections illustrated show these features and demonstrate that deposition occurred less as overbank than as in-channel deposits.

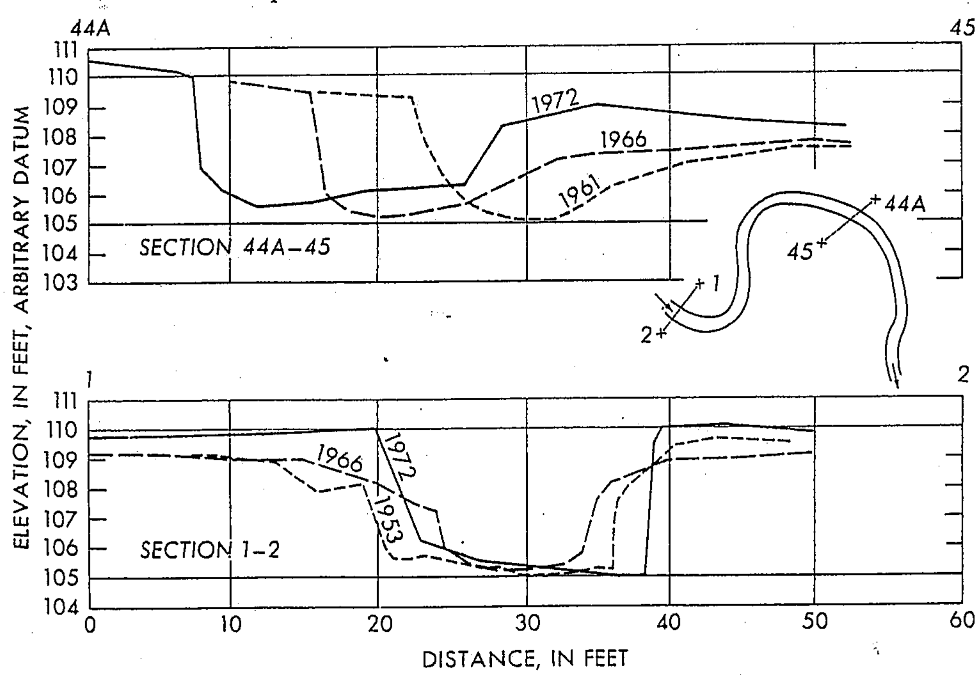


Figure 10. Selected cross sections of the channel of Branch at original date of survey, an intermediate , and 1972, section 44A–45 (upper) and section 1–2 (lower). Planimetric sketch (center) shows location of sections relative to channel bends.

Deposition in the channel was not confined to point bars convex in plan view. Section 15–17 (Fig. 11), for example progressively built both banks channelward, increasing the steepness at the same time. This occurred despite the fact that the section is located in the upstream part of a meander curve both before and after the artificial cutoff made by the sewer construction upstream in 1961.

To demonstrate that successive small rises, not large floods, account for the progressive alteration of channel, Figure 11 shows two successive surveys of section 1–4A in 1972. The surveys were made in April and September; between those surveys (in August), the largest flood of record occurred, associated with Hurricane Agnes. The section was changed so little that differences are within the usual limit of survey accuracy.

Figure 12 shows an example in section 35–34A of how a locally wide place, formerly a muddy point bar, built up to considerable height as the channel moved laterally. In the same figure, section 46–47 is an example of a place just upstream of a meander bend where the channel migrated not at all but built its banks higher by deposition, decreasing the width/depth ratio of bankfull stage.

## EFFECTS OF URBANIZATION

The change in average values obscures some salient details, the most important of which is the marked alteration in stream behavior that began about 1966. Channel cross-

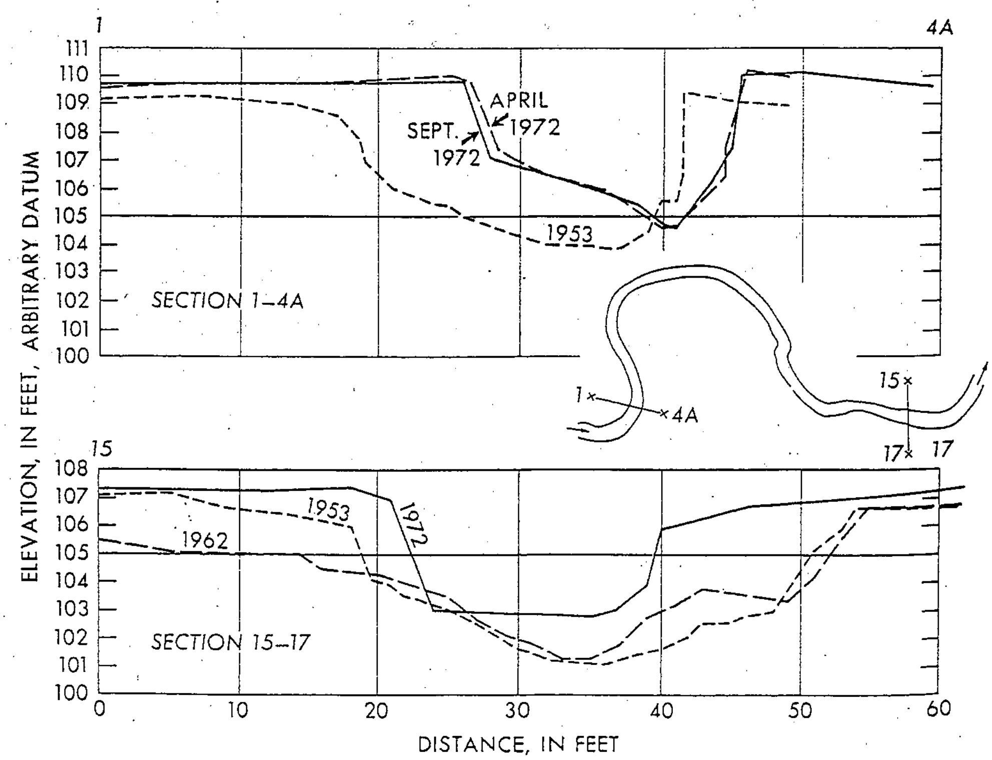


Figure 11. Selected cross sections of the channel of Watts Branch, section 1–4A (upper) and section 15–17 (lower).

sectional area for two sections is plotted against time in the upper graphs of Figure 13. In 1967 at section 44A–45, a large block of turf fell into the channel from the concave bank and caused a temporary decrease in local cross-sectional area and a rise in bed elevation. Otherwise, section 44A–45 shows a tendency for some increase in area in the years prior to 1967, and section 1–2 shows some decrease in area. From 1966 to 1972, the area increased markedly in nearly all sections of which the two depicted are representative. Most sections shared with 1–2 a tendency for some decrease in area prior to 1967.

The amounts of channel erosion and deposition from one survey to another are shown in the lower part of Figure 13 for the same sections. If the channel is migrating laterally, both erosion and deposition are large as in 44A–45. An excess of erosion over deposition in the same period causes an increase in cross-sectional area.

These progressive changes with time can be attributed to the various consequences of progressive urbanization of the basin. Though more sophisticated measures of degree of urbanization may be drawn from study of aerial photos, a simple measure is the number of buildings shown on a 7½′ topographic map published by the U.S. Geological Survey. Three editions of the Rockville, Maryland, sheet were available, and on each the number buildings shown was counted within the basin of Watts Branch. The results (Fig. 14) show a nearly linear increase from 1954 to 1965. The increase in buildings shown was five-fold. Until 1965, not more than three houses could be seen from that part of the valley

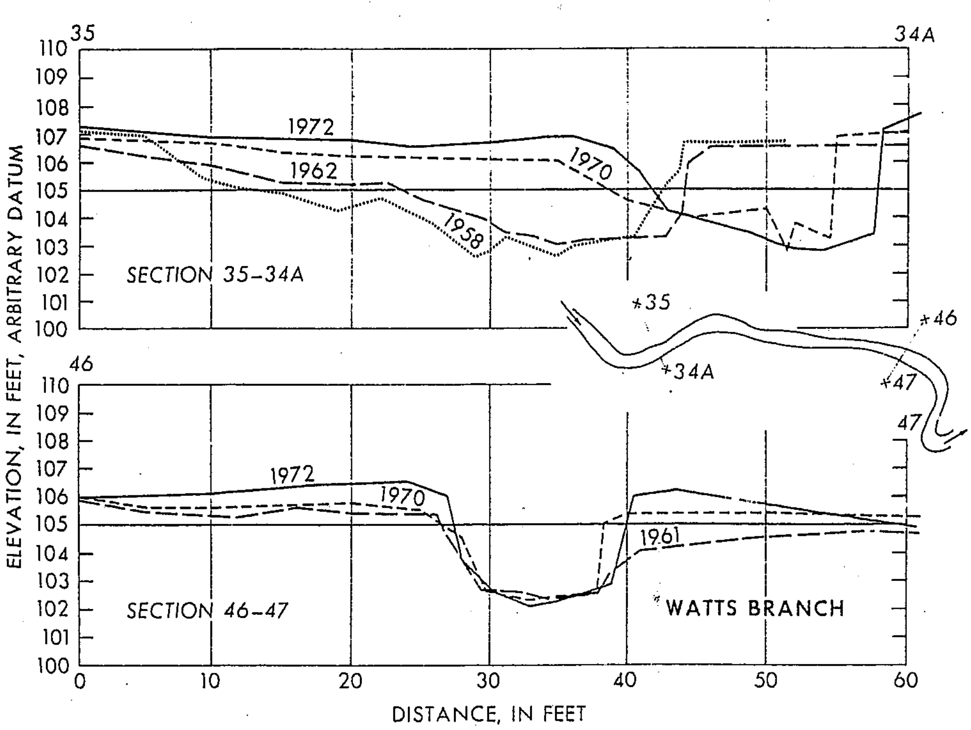


**Figure 12.** Selected cross sections of channel of Watts Branch, section 35–34A (upper) and section 46–47 (lower).

where the cross sections were established. In 1972, not less than 40 houses can be seen from the same place. When the farm on which the measurements were made was sold for development, grazing ceased and the valley flat became covered with willows near the channel and heavy herbaceous cover elsewhere. This increase in vegetation may have had some tendency to trap sediment during periods of overflow, but the massive deposits within the channel where such vegetation does not exist suggest that a large increase in sediment load rather than vegetation is the major cause of channel and overbank deposits.

During the period of observation, several large building complexes were developed in the upper part of the basin. A junior college and the county school administration headquarters were built, both with large paved parking areas. Much construction occurred within the city of Rockville. An interstate highway was built through the watershed area, including a cloverleaf interchange just upstream of the study reach.

Though I have taken enough suspended load samples in Watts Branch to develop a usable rating curve, the records are not sufficiently complete to show any change in load concentration for a given discharge. Records of water discharge, however, appear to show effects of urbanization. Figure 15 shows the recurrence interval for discharges

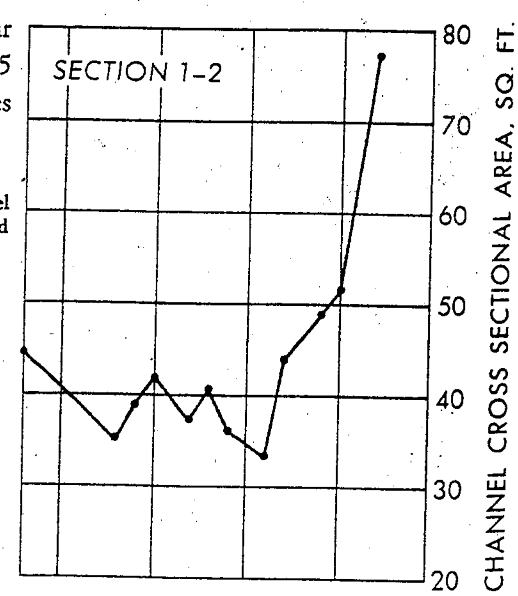
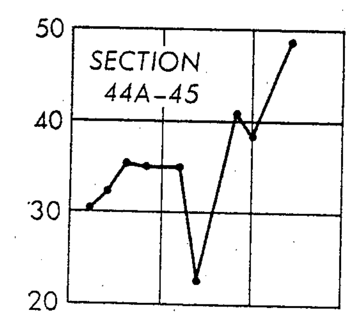
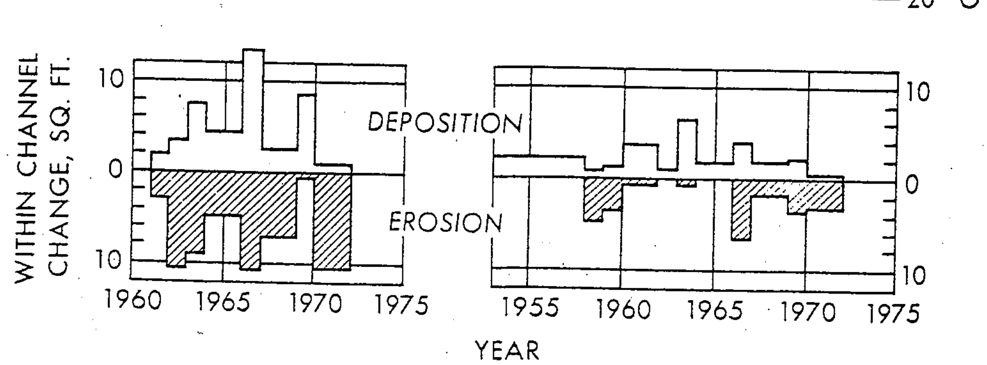


**Figure 13.** Progressive change with time of channel cross-sectional area (upper) and of channel erosion and deposition (lower) in sections 44A–45 and 1–2.

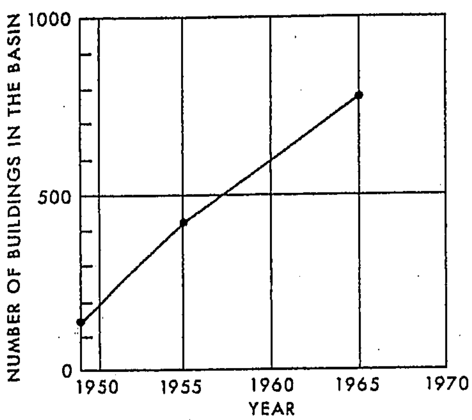


**Figure 14. Growth in urbanization in 3.7-sq-mi basin of Watts Branch indicated by the number of individual buildings shown on three successive editions of U.S. Geological Survey topographic maps.**

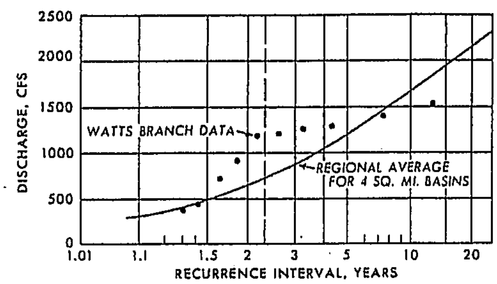


**Figure 15. Flood-frequency data for Watts Branch at Rockville; solid line shows the regional average for basins of similar size.**

of various sizes. The regional curve representing basins of the same size was taken from the flood frequency study of North Atlantic Slope Basins (Tice, 1968). The Watts Branch data represent annual floods recorded at the U.S. Geological Survey gaging tation near the study reach. The highest flows in the short record are commensurate with the regional expectancy, but flows of recurrence intervals of 1.5 to 5 yrs exceed the regional average by more than twofold. The mean annual flood for Watts Branch in the 12 yrs of record was 913 cfs, whereas the regional mean annual flood for basins of the same size is 700 cfs.

The best evidence that the deposition in the channel and on the valley floor and the observed flood experience are interrelated with urbanization is in the coincidence in time that changes took place.

Figure 16 shows the number of flows exceeding two chosen discharge values as a function of time. The figure 220 cfs was used because it represents the bankfull discharge at a straight and natural section when the observations began. As one would expect from previous studies of bankfull stage, this discharge might be expected to be equalled or exceeded about twice each year in a natural channel. Beginning in 1965, this expected number increased dramatically. So also did the number of flows exceeding 1,000 cfs, picked merely as illustrative of flows considerably above bankfull.

The frequency at which a stream overflows its banks is a function both of channel capacity and of frequency of flows of a given size. In the early part of the record, the channel cross-sectional area was slowly but progressively decreasing. In the later part of the record, the number of flows equal to or exceeding a given discharge increased markedly. On the basis of the average net decrease of channel area from the beginning to the end of the record, assuming that velocity at any given discharge did not change, the number of discharges that flowed overbank in the study reach was increased somewhat, as estimated Table 2.

During this record on this stream, it appears that the effect of urbanization on flow

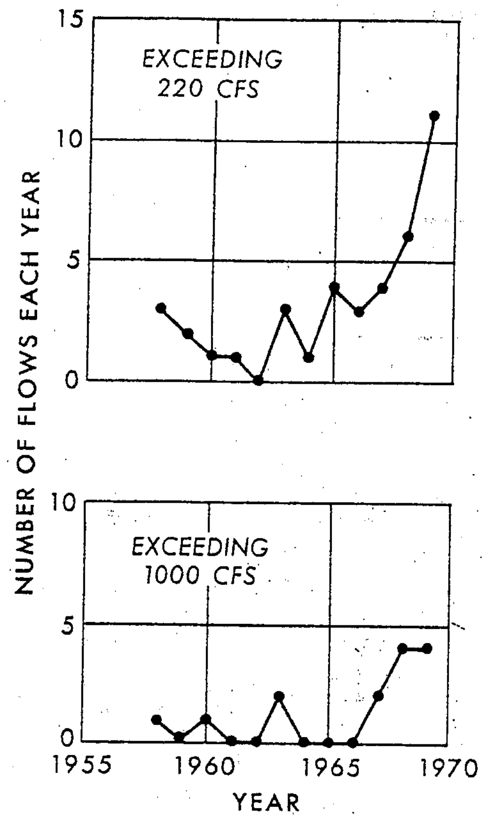


TABLE 2. NUMBER OF FLOW EVENTS EXCEEDING SPECIFIC LIMITS

| Year | Estimated bankfull capacity (cfs) | Number of flows exceeding 220 cfs | Number of flows exceeding channel capacity |
|---|---|---|---|
| 1958 | 220 | 3 | 3 |
| 1959 | 220 | 2 | 2 |
| 1960 | 215 | 1 | 1 |
| 1961 | 215 | 1 | 1 |
| 1962 | 210 | 0 | 0 |
| 1963 | 210 | 3 | 3 |
| 1964 | 205 | 1 | 1 |
| 1965 | 205 | 4 | 4 |
| 1966 | 200 | 3 | 3 |
| 1967 | 200 | 4 | 5 |
| 1968 | 195 | 6 | 7 |
| 1969 | 190 | 11 | 11 |

TABLE 3. ELEVATION OF GROUND SURFACE AND OF REFERENCE MARKERS LOCATED ON THE FLOOD PLAIN

| | 1959 | | 1972 | | |
|---|---|---|---|---|---|
| Pin no. | Pin elevation (ft) | Ground surface elevation (ft) | Pin elevation (ft) | Ground surface elevation (ft) | Deposition in 13 years (ft) |
| 1 | 111.86 | 111.90 | 111.82 | 112.70 | 0.8 ± 0.1 |
| 2 | 111.45 | 111.49 | 111.28 | 112.52 | 1.0 ± 0.2 |
| 3 | 111.31 | 111.35 | 111.14 | 111.94 | 0.6 ± 0.2 |

**Figure 16.** Number of flows equal to or exceeding two discharges, Watts Branch at Rockville, Maryland, as a function of time.

frequency is quantitatively a much more important determinant of frequency of overbank flooding than is the change of channel capacity.

Figure 17 presents data on ground-surface elevation at pins marking the cross sections. Nearly without exception, these are located 10 ft or more away from the channel. The vertical scale of elevation is relative, so that the data are merely separated enough to be read. Data are plotted to the nearest 0.1 ft which is about the random variation resulting from particular placement of the rod during the survey.

Note that there was no overbank deposition accumulating at any pin location in the first 10 to 12 yrs of record. But beginning in 1966, all showed deposition which grew progressively, and even at an increasing rate at some pins. There is, therefore, a coincidence in time of overbank deposition, increase in area of channel cross section, and increase in the number of high flows per year.

The deposition was not confined to the zone immediately next to the channel, but apparently occurred over the whole valley floor. Two types of evidence attest this. There is no obvious or apparent natural levee being developed near the stream margin. Direct evidence is available from the resurvey of three iron pins driven in 1959 and located on a line across the valley floor for the express purpose of determining the importance of overbank deposition away from the channel. These were ½-in. iron rods, 3 ft long, placed respectively 40, 117, and 165 ft from the stream where the river is near one side of the valley. The valley flat is at the place 350 ft wide. The pins were driven so the tops were 0.04 ft (½ in.) below the surface. The local ground surface was determined by laying a 6-in. ruler on the ground and using its elevation as the mean ground elevation at that place.

These pins were relocated and resurveyed for the first time in October 1972. The elevations are shown in Table 3.

For some reason, the pin elevations in 1972 were lower by as much as 0.17 ft than when installed, which probably was the result of a survey error in 1959. Nevertheless, the error is considerably smaller than the amount of deposition. I have listed in Table 3 the net deposition and followed it by a plus-or-minus figure representing the uncertainty. The conclusion is clear, however, that deposition over the valley floor was more than one-half foot in the 13 yrs, and from the cross-section data, most must have occurred since 1966.

In the first decade of observation, the channel area slowly contracted, and the spate of channel enlargement after 1966 had not by 1972 overcome the average decrease in channel area in the whole record. But the reversal from channel contraction to enlargement as the effects of urbanization intensify is what would be expected from the study of Hammer

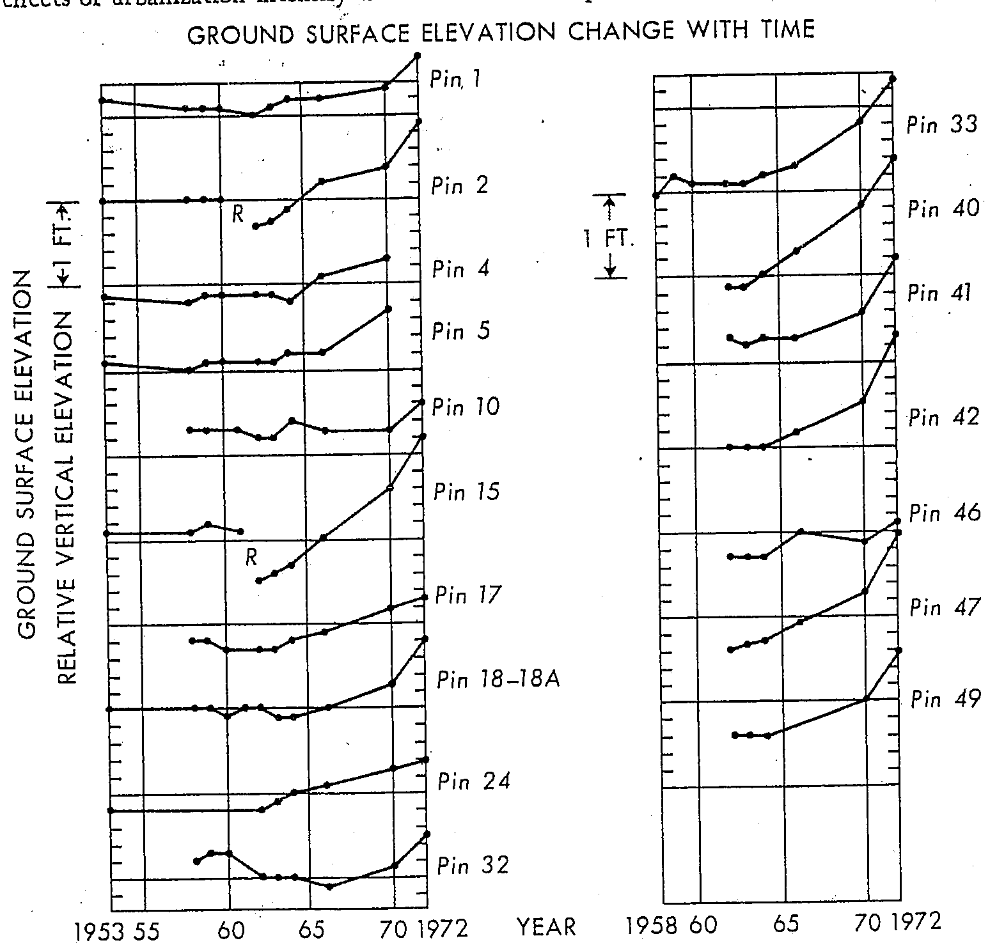


Figure 17. Ground-surface elevation change with time at location of pins monumenting the cross sections.

(1971). He measured channel cross section in 78 basins of 1 to 6 sq mi in area, and showed that channel enlargement is related to the degree of urbanization, the latter being measured by several parameters and in great detail. For a highly urbanized basin, channel area may be approximately double that of a natural basin. Figure 13 suggests that Watts Branch may be expected to continue enlargement of the channel and thus will fit into the pattern demonstrated by Hammer.

Though complete plane table maps of the channel were made only in 1953 and 1959, the progress of lateral channel movement can be traced by comparison of measured cross sections. There is no indication from these data that the rate of channel migration is altered by urbanization.

## INTERPRETIVE COMMENT

As suburban growth continues apace, its subtle and delayed effects on the river environment—rate of process, characteristics of channels and flood plains, sediment movement, and aesthetic values—are going to be affecting more areas and more people. In the small basin discussed here, the picnic places where I took my children are now muddy trash heaps. Where we played catch, there is now a shrubby and scrubby jungle. The little stream is littered with bricks, concrete trash, plastic bottles, and old tires. Nearby, new and expensive houses look out on a brown mudhole in a small silt-control basin constructed by the builder.

If we are to devise ways in which urban development may proceed with a minimum of these adverse effects, we must have facts—observations made on the ground documenting effects of particular actions. Our present programs of river observation concentrate primarily on flow records and, much less intensively, on water-quality determinations. But the facts needed in the face of city growth go far beyond these network observations. We must begin to see the river as a whole—or reaches of river as a unit. A river is far more than the water it contains.

The information required is not necessarily complicated or costly. A few days of work a year can sustain a valuable observation program, if continued through a span of years. Yields can be both in theoretical knowledge of process as well as practical knowledge for design. Geologists, more so than most people, know how the natural world operates and what beauty lies in these mechanisms of nature. If some of the beauty of undisturbed processes is to exist within the reach of cities, the present practices of planning, design, and construction must include some geologic knowledge. That knowledge can come only from us.

## ACKNOWLEDGMENTS

The work of surveying and shoveling, mixed with the pleasure of good company and interesting conversation, was shared with William W. Emmett, Robert M. Myrick, George Dury, John Troxell, Bruce Lium, Garnett Williams, M. Gordon Wolman, Ran Gerson, and others. Their co-operation through the years has been appreciated.

*[At this point in his oral presentation, Dr. Leopold said that he wished to conclude with a few words about the general problem of environmental degradation (in calypso time).]*

*(second verse)*

Gotta beat the Russians at the technical race,
The real reason is we're going to run out of space.
We're the only ones who put a man on the moon,
And most of us are planning on moving there soon.
Our industrial capacity never does sleep
So you know what is piling higher and deep,
And so from a logical point of view,
Ya better get the garbage before it gets you.

*(third verse)*

Da country is bad but science is worse,
A proliferation of words is our curse,
Nobody ask if ya got sometink to say,
Ya gotta write a paper to get your pay.
Scientific laboratories none but the best,
Never see the field so ya just gotta guess.
And so from a logical point of view,
Ya better get the garbage before it gets you.

*(fourth verse)*

Industry likes to look underground,
But they never tell ya just what they found.
All their reports are classified,
It must mean they got lots of things they must hide.
Their files are so full of junk and of crud,
They never even know when the well was a dud.
And so from a logical point of view,
Ya gotta get the garbage before it gets you.

*(fifth verse)*

Ground water once was the Survey's pride,
On Meinzer's reputation the whole thing ride,
Now all reports sound just the same,
Geology and ground water some county name.
From Darton and Gilluly they steal all their maps
And then they wonder why ther'e so damn many gaps.
So from a logical point of view,
Ya better get the garbage, ya better get the garbage,
Ya gotta get the garbage before it gets you.

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# Stream Response To Stormwater Management Best Management Practices In Maryland

**Final Deliverable**
**U. S. Environmental Protection Agency**
**Section 319(h), Clean Water Act**
**July, 2000**

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# Stream Response to Stormwater Best Management Practices in Maryland

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**Stream Response to Stormwater**
**Best Management Practices in Maryland**

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## LIST OF FIGURES



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# Stream Response to Stormwater Best Management Practices in Maryland

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This project was made possible through funding provided by the U.S. Environmental Protection Agency (U.S. EPA), under the Section 319 Nonpoint Source Program. This is a cooperative effort between the Maryland Department of the Environment's Water Management Administration (WMA) and Technical Assistance and Regulatory Services Administration (TARSA). Tom Tapley, Wayne Jenkins, Angelica Gutierrez and Christine Shannon (TARSA) provided valuable assistance during project development and watershed modeling activities. William Page and Melissa Frank (WMA) also contributed to the modeling component of this project.

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While the combined efforts from these people have been instrumental in the completion of this project, many people continue to provide support and inspire ideas to further the understanding gained herein. Thank you to all who continue in these efforts.

# Stream Response to Stormwater Best Management Practices in Maryland

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## ABSTRACT

The primary objective of this report is to evaluate stormwater management strategies and determine their effectiveness for protecting receiving stream channels. This was done by developing a watershed model of the Benson Branch watershed, in Howard County, Maryland. The data used for model development were collected in the field between 1996 and 1998, and reported in MDE, 1999. Results of the stormwater management modeling indicate that the channel protection volume ($Cp_v$), (MDE, 2000) and the Distributed Runoff Control (DRC) methods (MacRae, 1993 and Ontario Ministry of the Environment, 1999) provide a similar level of management for the ponds simulated in this watershed. The highest level of control for both practices is focused on flows in the mid-bankfull range.

An evaluation of stream channel thresholds is provided to more completely analyze stormwater management strategies. A release of stormwater runoff below the stable channel threshold results in minimal impact on the stream channel. Using the stability analysis, the $Cp_v$ and DRC designs could protect the streams monitored in this study for storms less than 2.0" of rain, generally falling over a 24 hour period. Given that streams are highly variable with respect to hydrology and morphological stability thresholds, a site specific stream morphology study will improve efforts in evaluating the effectiveness of management strategies for stream channel protection.

Guidelines for evaluating stormwater management designs for stream channel protection are provided herein. The guidelines focus on evaluating receiving stream geomorphology and identification of stability thresholds. The results and implications found in this study pertain to the Benson Branch watershed in Howard County, Maryland. Using the guidelines to evaluate other streams in Maryland will expand the data set so that implications of these results may be applied on a broader scale.

## INTRODUCTION

Maryland's current stormwater management program was developed during the early 1980's when flood control was the primary issue concerning urban runoff management. Prevailing experience had indicated that when flooding, caused by increases in runoff volume from new development could be controlled then the quality of receiving streams could be sustained. Consequently, the design criteria for the original Code of Maryland Regulations (COMAR) regulating stormwater runoff was to manage the release of peak flows for the 2 and 10 year design storms so that pre-development peak flows would not be exceeded.

After many years of experience on stormwater management implementation across Maryland, MDE has found that management of peak flows for the 2 and 10 year storms does not provide sufficient stream channel erosion protection from the increased runoff caused by urbanization. As a result, MDE has proposed revisions to COMAR concerning stormwater to refocus overall objectives toward controlling more frequent storm events, prevent stream channel erosion, and create incentives for developers to design projects in an environmentally sensitive manner. The 2000 Maryland Stormwater Design Manual, Volumes I and II is an integral component of these revisions. As part of the manual, extended detention of the 1 year 24 hour storm ($Cp_v$) is the design criteria for protecting stream channels.

This project provides an in-depth analysis of stormwater management strategies to determine their effectiveness in protecting stream channels. The project's Phase 1 deliverable (MDE, 1999) provided an assessment of the Benson Branch watershed in Howard County, Maryland. Using this assessment, a Hydrology Simulation Program – Fortran (HSPF) model was developed to simulate different stormwater management strategies to analyze their effectiveness for protecting the receiving stream channel. An evaluation of stream channel thresholds is included to more effectively evaluate the various management strategies.

The overall goal for this project is to propose and evaluate stormwater management strategies to determine their effectiveness at protecting stream channels. To this end, a summary of required data sets and analytical procedures is presented for development and evaluation of stormwater designs. These procedures may be applied to other watersheds in Maryland to evaluate the effectiveness of stormwater management designs for maintaining stream channel stability.

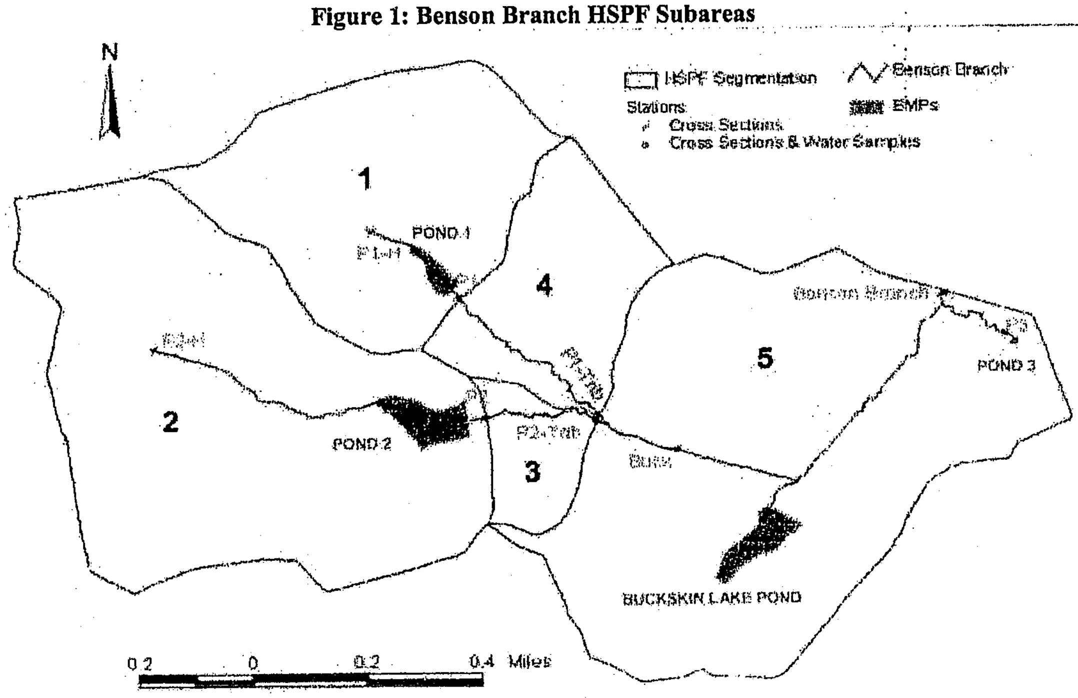
## HSPF MODEL DEVELOPMENT

HSPF simulates hydrology processes that occur in a watershed by using information such as time, history of rainfall, temperature, evaporation and parameters related to land use and soil characteristics. The Phase I deliverable (MDE, 1999) information concerning stream morphology provides the foundation for the development of an HSPF model for the Benson Branch watershed in Howard County, Maryland. Model output is a time history of runoff flow rate and water quality constituents in the watershed (Donigian, Jr., et. al, 1995). Development of this model is a collaborative effort between MDE's Technical and Regulatory Services Administration (TARSA), and the Water Management Administration (WMA). TARSA initially constructed the model by developing user control input (UCI) files, and compiling the necessary meteorological information. WMA used these files in the U.S. EPA software program, Better Assessment Science for Integrating Nonpoint Sources (BASINS). BASINS utilizes a geographic information system (GIS) and a Windows interface for running HSPF. In this way, WMA was able to make field verified adjustments to the model and analyze stormwater management scenarios on the watersheds flow regime.

<u>Model Input</u>

The Benson Branch watershed, a 1.22 square mile drainage area, is a tributary to the Middle Patuxent River located in Howard County, Maryland. To facilitate the HSPF modeling, this watershed was divided into five subareas shown in Figure 1 below. Subareas 1 and 2 make up the land area contributing to Ponds 1 and 2 (MDE, 1999), while subarea 5 is the most downstream study point.

**Figure 1: Benson Branch HSPF Subareas**



Land use data calculated for each of the 5 subareas using ArcView 3.0/GIS Software include: forested, agricultural, pervious urban, impervious urban and stormwater ponds. A summary of the information is presented in Table 1.

**Table 1: Land Use by HSPF Segment for the Benson Branch Watershed**

UNITS: Acres

| SUBAREA | FOREST | AGRICULTURE | PERVIOUS URBAN | IMPERVIOUS URBAN | STORMWATER PONDS | TOTAL LAND |
|---|---|---|---|---|---|---|
| 1 | 130.63 | 22.74 | 78.83 | 12.36 | 5.79 | 250.35 |
| 2 | 38.51 | 3.71 | 75.81 | 10.04 | 2.00 | 130.07 |
| 3 | 21.22 | 0.00 | 2.12 | 0.23 | 0.00 | 23.57 |
| 4 | 23.49 | 7.47 | 32.42 | 3.51 | 0.00 | 66.89 |
| 5 | 153.11 | 63.30 | 76.10 | 9.02 | 5.35 | 306.88 |
| **TOTAL** | **366.96** | **97.22** | **265.28** | **35.16** | **13.14** | **777.76** |

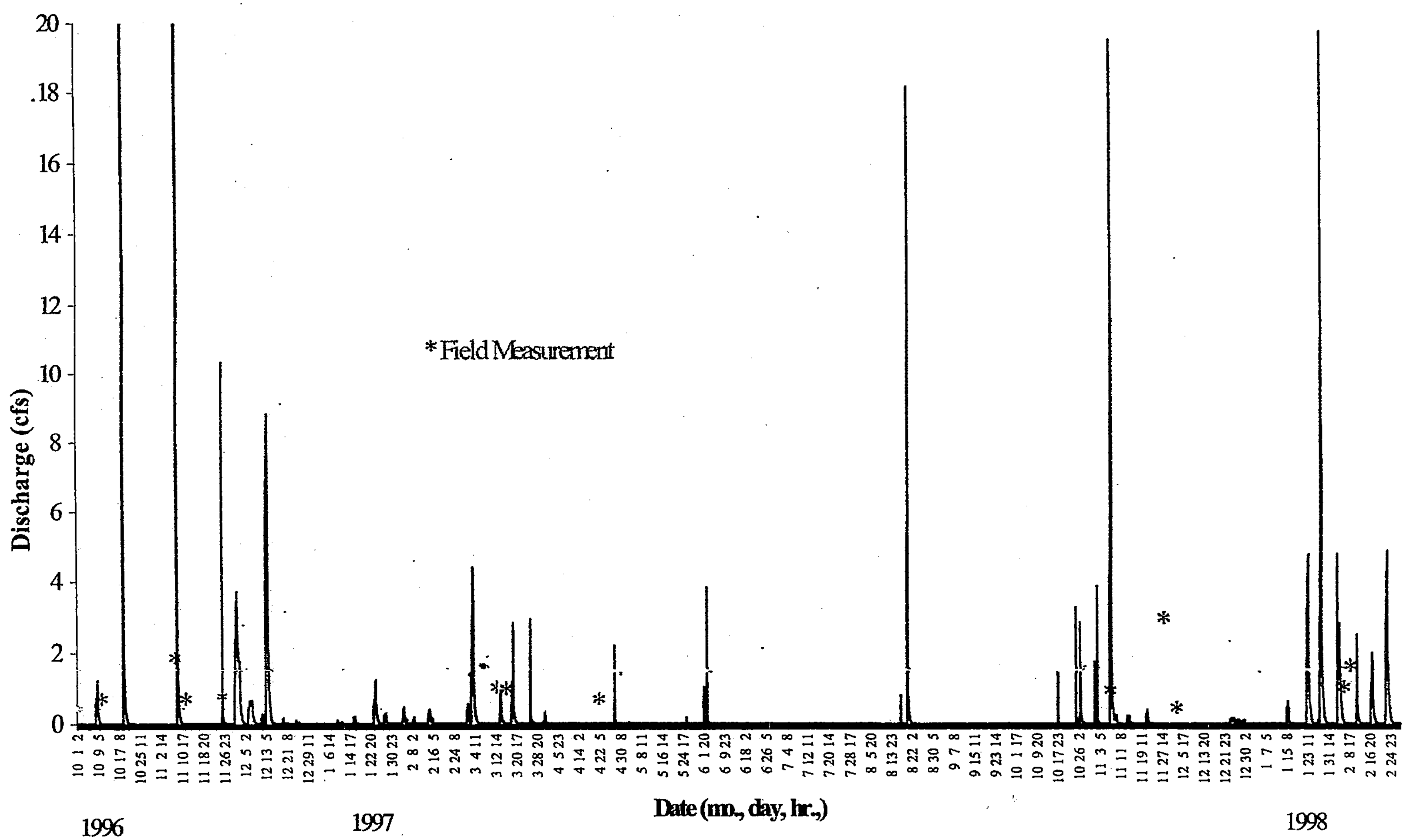
The HSPF model uses a hydraulic function table, (F-TABLE), to represent the geometric and hydraulic properties of a stream reach and fully mixed reservoirs (U.S. EPA, 1999a). The F-TABLE defines a linear relationship between water depth, surface area, volume and outflow, to establish a stage-discharge relationship within the stream reach. An F-TABLE is developed for each of the stream reaches located in the five subareas. The stream reaches are then labeled corresponding to the subarea it is located in (i.e. Reach 1 is located in subarea 1, etc.).

F-TABLES in Reaches 1 and 2 are based on the hydraulic characteristics at the outflow of Ponds 1 and 2. Reaches 3, 4 and 5 F-TABLES were developed using WINXSPRO, a channel cross-section analyzer software package (U.S. Forest Service, 1977). WINXSPRO develops a stage-discharge relationship by synthesizing stream cross-section information, reach slope, and roughness data. F-TABLES for each reach are summarized in Appendix 1.

Model Calibration

Hydrologic parameters input into the BASINS model generally describe soil processes, groundwater flow paths and evapotranspiration for each land use. The U.S. EPA BASINS Technical Note 6 (U.S. EPA, 1999c) provides guidelines for estimating these parameters based on watershed conditions. In addition, the U.S. EPA website (www.epa.gov/ost/basins/support/htm) offers the HSPFParm database (U.S. EPA, 1999d) which tabulates parameter values under a variety of watershed conditions from previous applications across North America. These sources aided in the initial determination of appropriate ranges of input parameters based on watershed conditions. Later they were also used to calibrate the model with field data. Figure 2 shows the time series of runoff flow rate for the subarea below Pond 1, called Reach 1, with the observed flow rates indicated where available. Appendix B shows the time series for the remaining segments in the Benson Branch watershed. Appendix C contains a sensitivity analysis that indicates the range of variation of model output for those parameters found to affect the model most significantly.

**Figure 2**
**Reach 1, Below Pond 1**

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## HSPF AND TR-20 MODELS

This section compares results from the HSPF and Technical Release 20 (TR-20) hydrology models. TR-20 (Natural Resources Conservation Service, 1982) is a single event model which computes runoff resulting from a rain storm. Comparing these two models was of interest because TR-20 is most often used for stormwater management designs, however, the HSPF model offers a more detailed account of watershed conditions.

The TR-20 model provides a simple rainfall – runoff relationship based on watershed area, land use, and drainage area characteristics. While TR-20 is relatively simple to use, the model underestimates runoff from rainfall less than the two-year storm event (which is about 3.2 inches of rainfall over 24 hours in the Baltimore metropolitan region). Another disadvantage of TR-20 is that a single parameter is used to represent the antecedent moisture condition. As a result, the accuracy of model output depends on the applicability of this initial assumption over a wide range of seasonal conditions.

HSPF has a wider range of applications and includes tools for watershed planning, problem solving, future development and resource protection strategies. HSPF determines initial conditions more precisely than TR-20 because it uses a continuous account of basin moisture modeled over an extended period of time. HSPF simulates surface, interflow and groundwater flows, while TR-20 omits subsurface flows as well as evapotranspiration (www.hydrocomp.com). A disadvantage of HSPF is that most of the parameters representing soil moisture conditions cannot be measured in the field, requiring estimates instead. Therefore, the accuracy of HSPF is dependent upon the accuracy of estimated soil moisture parameters. In referencing the Sensitivity Analysis in Appendix C, it is clear that a slight change in some of these parameters will cause a significant change in model output.

When using HSPF to model small watersheds, like the Benson Branch watershed (drainage area of 1.22 square miles), most of the streamflow observed from the stormflow hydrograph is a result of surface runoff. This is one possible reason that the HSPF model indicated low baseflow at the downstream most point in the watershed. Approximately 1.0 cfs of baseflow was measured or observed during the wet season and greater than 0.5 cfs during the dry season. Therefore, when using HSPF to model stormwater management practices in small watersheds, water movement through subsurface zones is generally not accounted for and this may affect the accuracy of the model.

Because, TR-20 is event based, the best way to compare the two models is to look at specific storms over the period of simulation. A total of 8 storm events are shown in Figure 3 to demonstrate trends and compare the results of the two models with observed flow measurements. The results of this comparison for the most downstream site on Reach 5 (see Figure 3) show the output hydrographs, precipitation data, and observed flows. The shape of the hydrographs and trends observed at Reach 5 also apply to other reaches, when comparing the two models at the upstream locations.

Field flow measurements for the eight storm events in Figure 3 are not continuous, rendering it difficult to determine which model is more accurate. However, the following trends may be observed:

1. Peak flows and runoff volumes from HSPF are generally greater than those from TR-20.

2. Larger storms show a wider variation in peak flows.

3. Differences between the two models are not significant for small storms.

4. Observed flow measurements generally lie between the two models but appear to be closer to HSPF.

Due to the wide variation of duration and total precipitation, it is difficult to identify consistent trends among the hydrographs. For example, the February 4 – 5, 1998 event occurred over 40 hours, and because this was a significantly longer duration than other observed events, some of the trends described above may not apply to this storm. The total runoff volume for the HSPF model exceeded that of the TR-20 run, however, storm flows toward the end of the rainstorm were actually higher for TR-20 than for HSPF. In addition, the November 25 – 26, 1996 rainfall was only 1.04 inches, versus the 1.62 inches for the February storm. However, the peak flows for the November storm were significantly higher than the February storm. It is believed that these inconsistencies are associated with the wide range of duration of precipitation events.

Continuous flow measurements would allow better information to evaluate the accuracy of the models. The models do appear to be relatively close for small storms and field measurements lie between the two models. In the following section, the HSPF model is used for evaluating stormwater management scenarios and stream channel erosion control in the Benson Branch watershed.

**Figure 3. Comparison of HSPF and TR-20 at Selected Rainfall Events**
**Reach 5, Benson Branch**

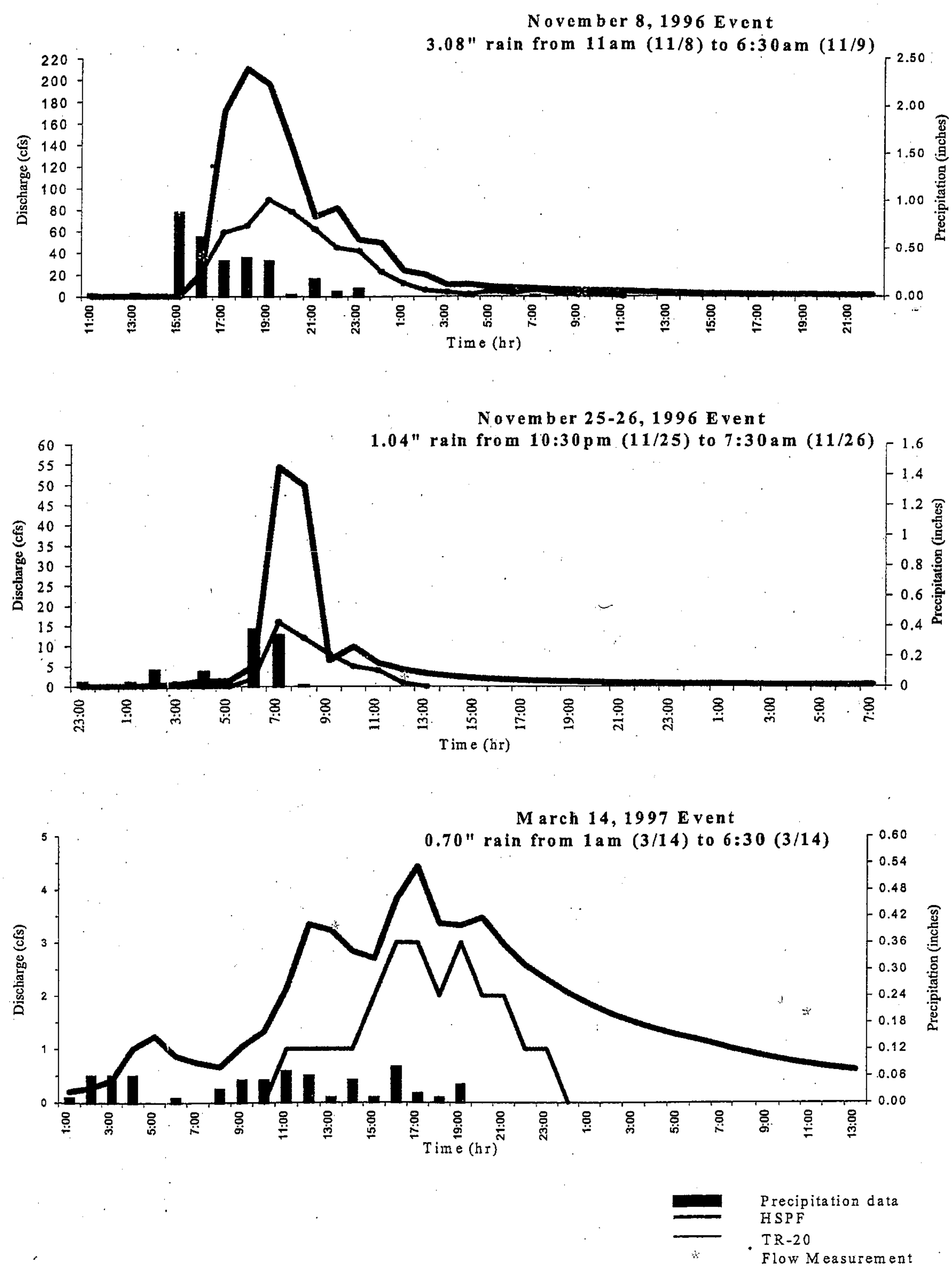

**Figure 3. Comparison of HSPF and TR-20 at Selected Rainfall Events**
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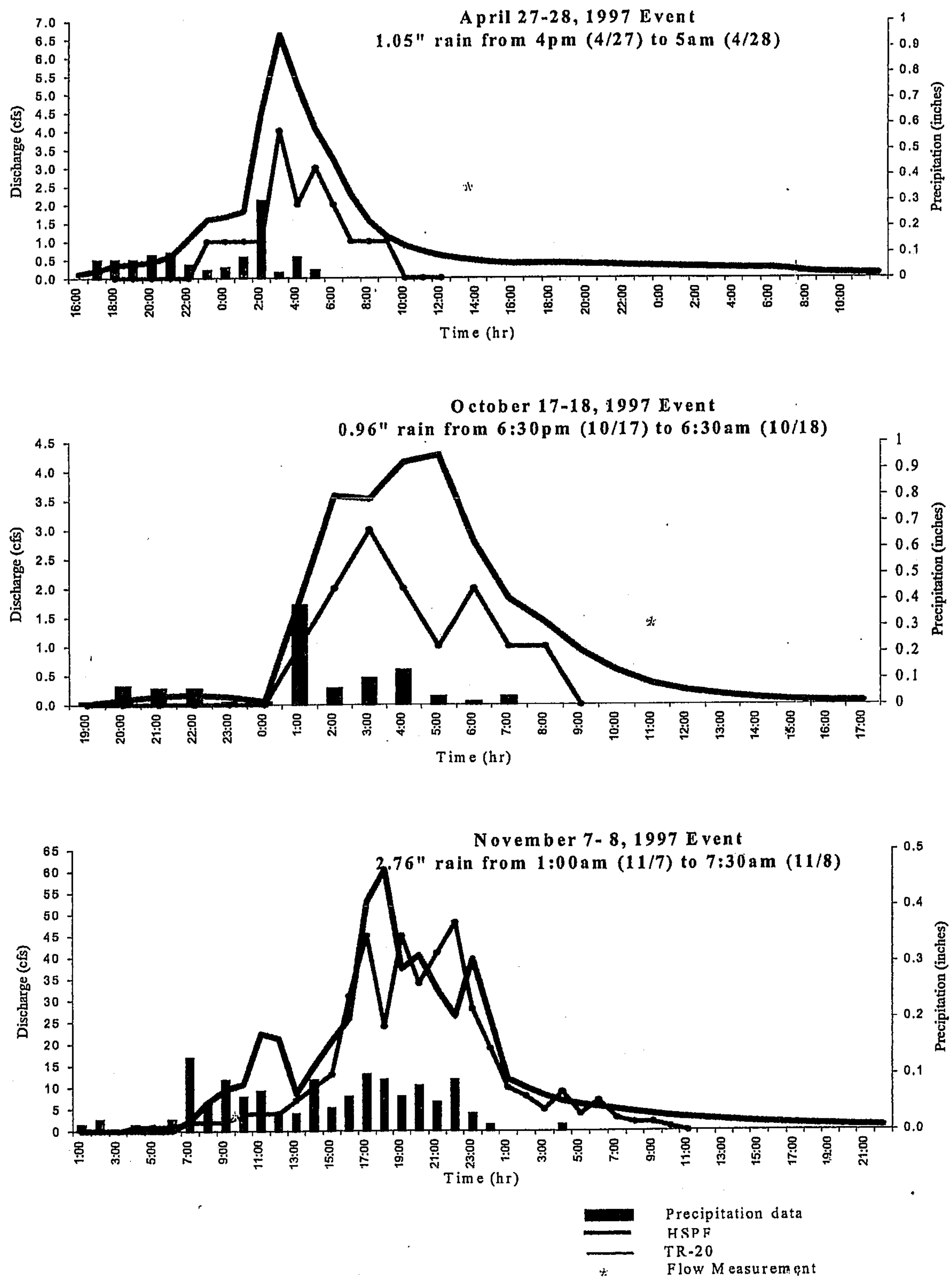
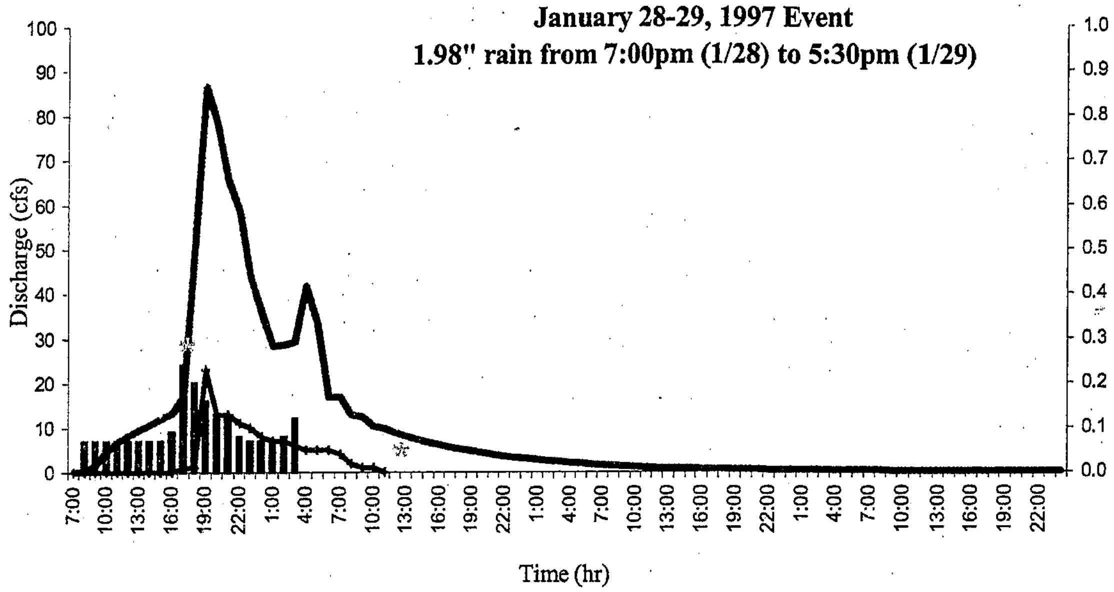
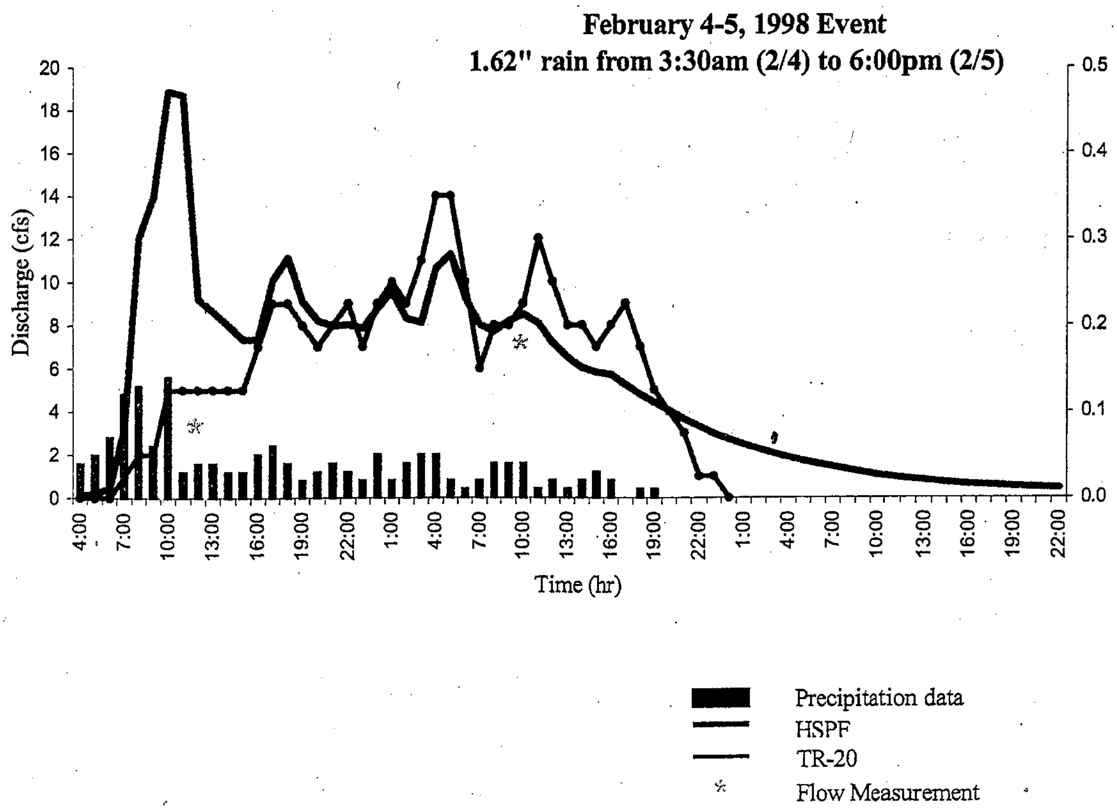


# Figure 3. Comparison of HSPF and TR-20 at Selected Rainfall Events
## Reach 5, Benson Branch



## STORMWATER MANAGEMENT SCENARIOS

### Scenario Development

The main objective in developing an HSPF model for the Benson Branch watershed is to evaluate the effectiveness of various management strategies for protecting stream channels. Using HSPF, four stormwater management designs are simulated for Pond 1 and Pond 2. The designs include existing ponds, 2 year peak management, channel protection volume ($Cp_v$), and the Distributed Runoff Control method (DRC). The designs are evaluated to model the effects of the duration of runoff on the receiving stream channel and to determine the most effective protection practice.

The first pond scenario represents existing watershed conditions. Ponds 1 and 2 were constructed for flood control and irrigation and do not meet current stormwater management regulatory requirements. Computations do show, however, that both ponds provide management for the 10 year storm. Stage-storage-discharge relationships (see the F-TABLES in Appendix A) represent the existing ponds.

The 2 year management design is based on attenuating discharges so that the pre-development peak flow for the 2 year, 24 hour storm event is not exceeded under post development conditions. The storage capacity required to maintain peak flows below a specified discharge is determined using the procedure outlined in Chapter 6 of the Technical Release 55 (TR-55) manual published by the NRCS. This establishes a new storage volume-discharge relationship. F-TABLES for the HSPF model are modified for the reaches below Ponds 1 and 2 (Reaches 1 and 2 respectively) to represent this new relationship, and are shown in Appendix A.

The $Cp_v$ scenario is based on a 24 hour delay between the centroids of the inflow and outflow hydrographs for the 1 year frequency storm. The design procedure follows the methodology outlined in MDE's *Design Procedures For Stormwater Management Extended Detention Structures* (MDE, 1987a). A new stage-storage-discharge relationship was established for Reaches 1 and 2 for the channel protection design and shown in the F-TABLES in Appendix A.

The State of Maryland is proposing the $Cp_v$ design for stream channel protection in the 2000 Maryland Stormwater Design Manual Volume I and II (MDE, 2000). This is significant because only one percent of all annual events will exceed the 1 year frequency storm (MDE, 2000). The philosophy is to provide attenuation for the more frequent storm events so that these discharges will be released at a rate that critical erosive velocities will seldom be exceeded. Using this procedure, peak outflow discharge is based on drainage area characteristics, and time of concentration in the watershed. The channel protection criteria using this method however, does not account for channel morphology or the composition of bed materials in the receiving stream.

The last procedure used for this analysis is called the Distributed Runoff Control (DRC) method, so named because of the non-uniform distribution of storage by stage (MacRae, 1993). The intent of the DRC approach is to minimize the potential for instream erosion for a range of flows from critical flow exceedance to the bankfull stage. The highest level of control is focused on flows in the mid-bankfull range. The revised stage-storage-discharge relationship, shown in the F-TABLEs in Appendix A is developed using the design procedure for the DRC method outlined in the Ontario Ministry of the Environment's draft Stormwater Management Planning and Design Manual (Ontario Ministry of the Environment, 1999).

The DRC method uses an overcontrol approach for flows up to bankfull. The amount of overcontrol is related to the boundary material composition of the receiving stream channel. Generally, the overcontrol ranges from 70% to 90% over the 2 year management release rate. In developing the modified F-TABLES for the DRC method, 80% overcontrol was provided. This was done by multiplying the allowable discharge for the 2 year storm by 0.2 for flows below the bankfull discharge. In short, this method incorporates characteristics of the receiving stream channel to develop an erosion control strategy, however, the data requirements are more intensive than the $Cp_v$ design.

Evaluation of Scenarios

A total of 9 storms are evaluated using HSPF to determine effectiveness of the four management strategies in protecting the stream channels at Reaches 1 and 2. Results for Reach 2 are shown in Figure 4. In general, trends observed with the scenario results at Reach 2 were similar to those found for Reach 1. Results for Reach 1 and the downstream most site at Benson Branch are included in Appendix D. The observed storms range from one to three inches of rainfall generally within 24 hours, while storm duration varies.

In general, there is little variation among the practices for storms above 2 inches of precipitation (3.08 inches for the November 8, 1996, 2.73 inches December 13, 1996, and 2.76 inches on November 7, 1997). Two storms were observed with approximately two inches of rain (August 20, 1997 and January 20, 1998). In both cases, the $CP_v$ and DRC practices show longer response times before flow enters the stream channel and increased levels of peak flow attenuation below the 2 year management and existing pond designs.

The February 4-5, 1998 storm delivered 1.62 inches of rain, with a resulting peak flow of only 5 cubic feet per second (cfs). This is much lower than other storms of lesser rainfall, due to the long duration of rainfall. This storm occurred over a 40 hour period, causing the runoff to enter the stream channel more slowly than a more intense storm.

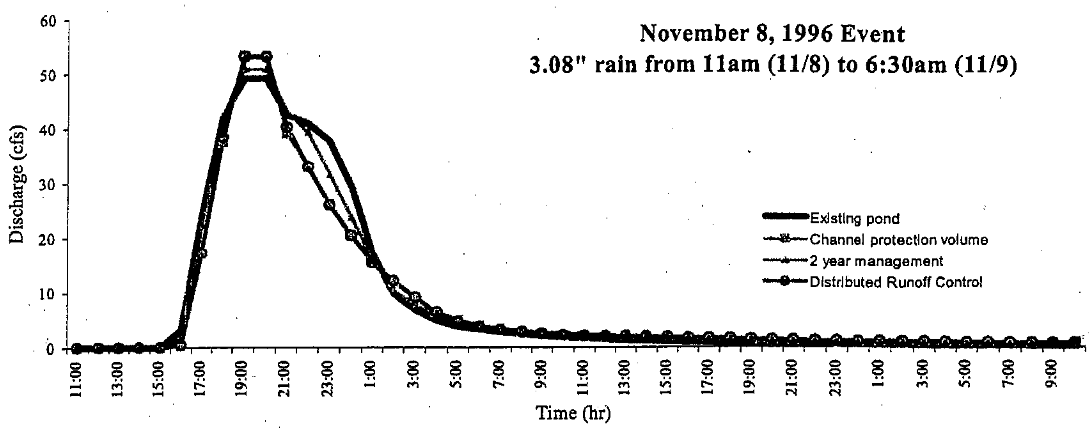
Three storms of approximately one inch of rainfall show the most significant differences among the various scenarios. The first, November 25, 1996, rained 1.04 inches over 9 hours, with the majority falling in a 2 hour period. This is the most intense of the one inch storms recorded during this project, and also had the highest streamflows. The peak discharge for the existing pond was about 12 cfs. However, the $Cp_v$ and DRC scenarios did not exceed 4 cfs. The other two storms showed a release of less than 0.5 cfs for the $Cp_v$ and the DRC designs.

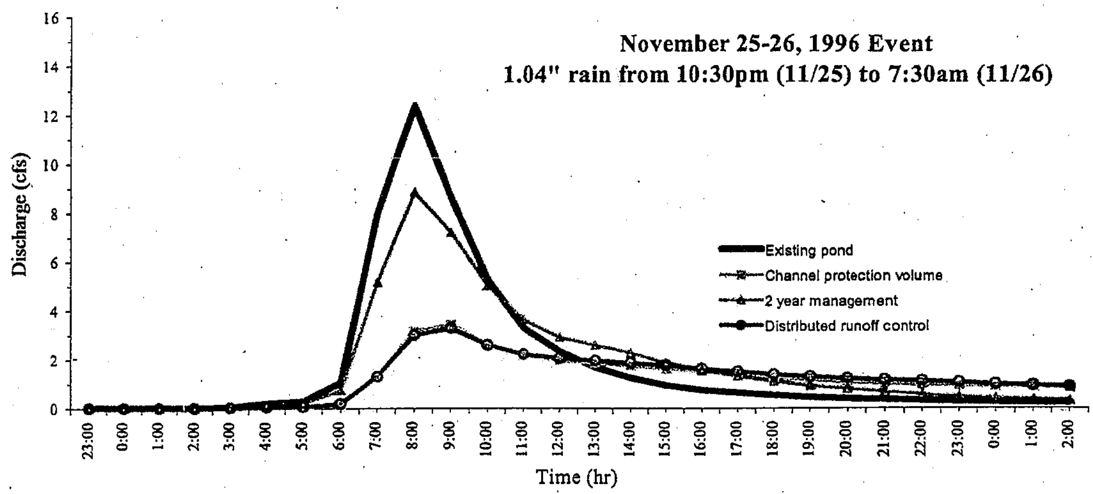
Streamflow hydrograph observations for the various stormwater management scenarios may be summarized as follows:

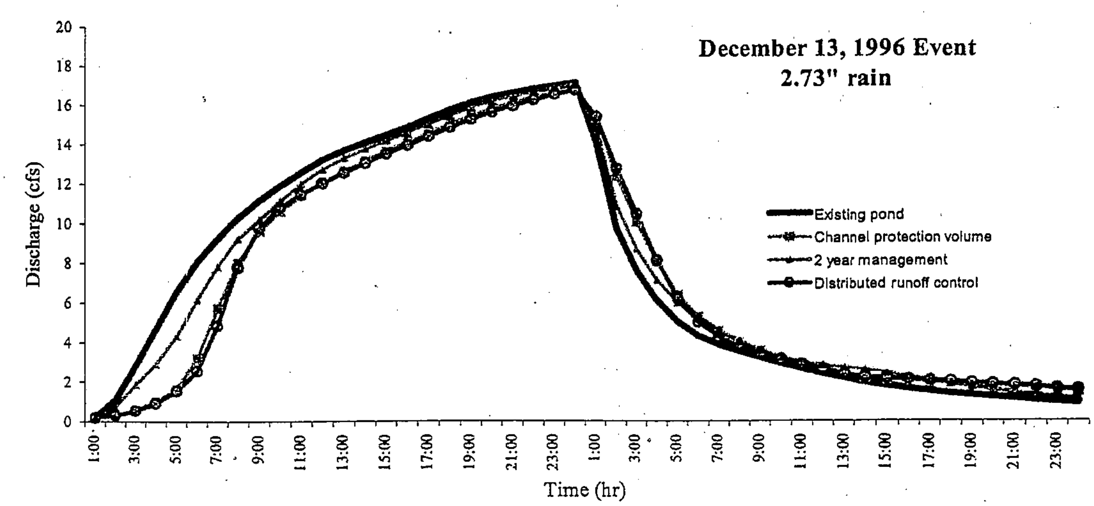
1. Hydrographs for the $Cp_v$ and DRC designs are not significantly different for the storms observed. Accordingly, the $Cp_v$ and DRC designs offer the same degree of channel protection for the two ponds observed in this study.
2. The $Cp_v$ and DRC methods provide the greatest protection for storms with less than 2 inches of rainfall. For storms greater than 2 inches, the $Cp_v$ and DRC hydrographs resemble the hydrographs for the existing pond and 2 year management scenarios.

This analysis focuses on comparing stormflow hydrographs under various scenarios. The next section provides an analysis of channel stability thresholds, to determine the effectiveness of various designs in protecting stream channels. Channel stability thresholds are based on channel morphology and stream bed composition.

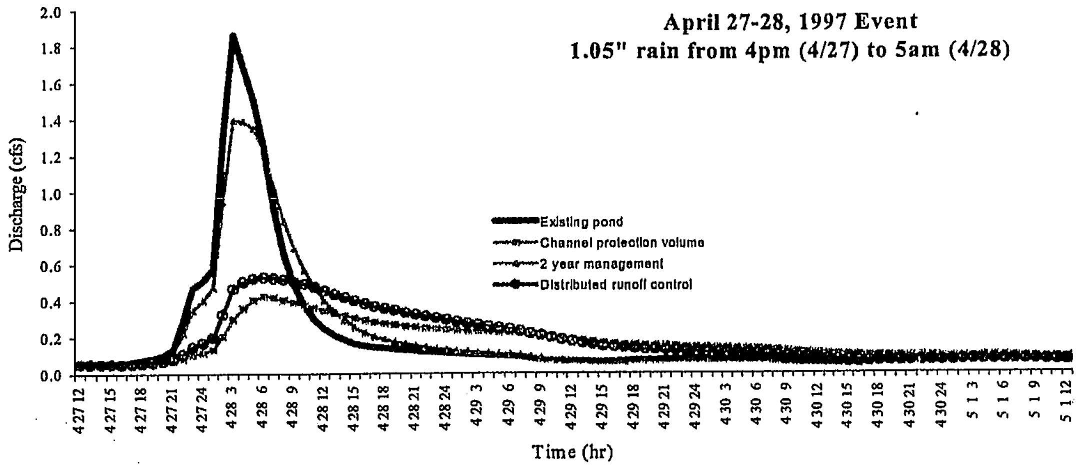
**Figure 4: Stormwater Management Scenarios**
**Reach 2, Below Pond 2**

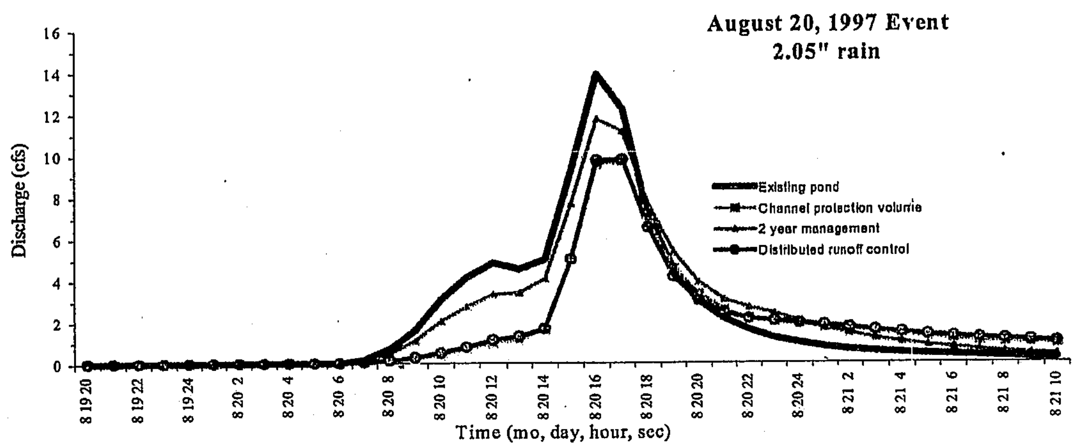


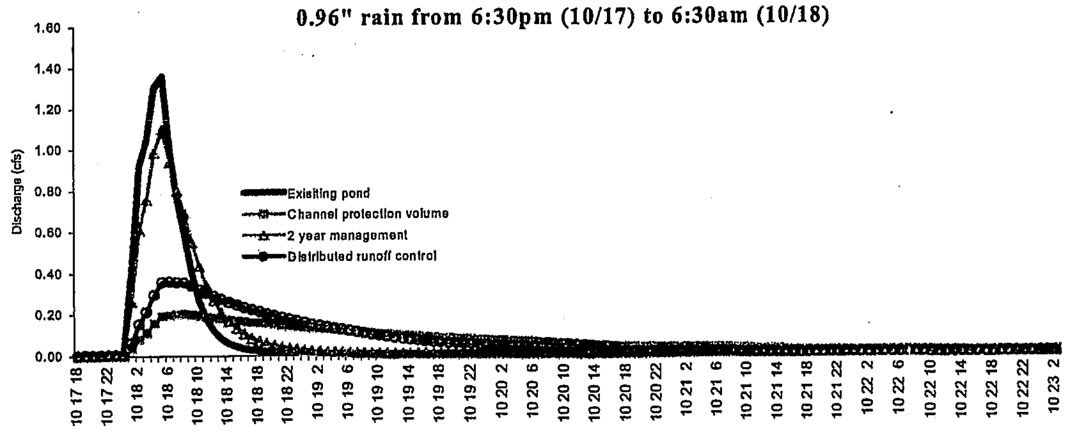



## STORMWATER MANAGEMENT SCENARIOS
## Reach 2, Below Pond 2

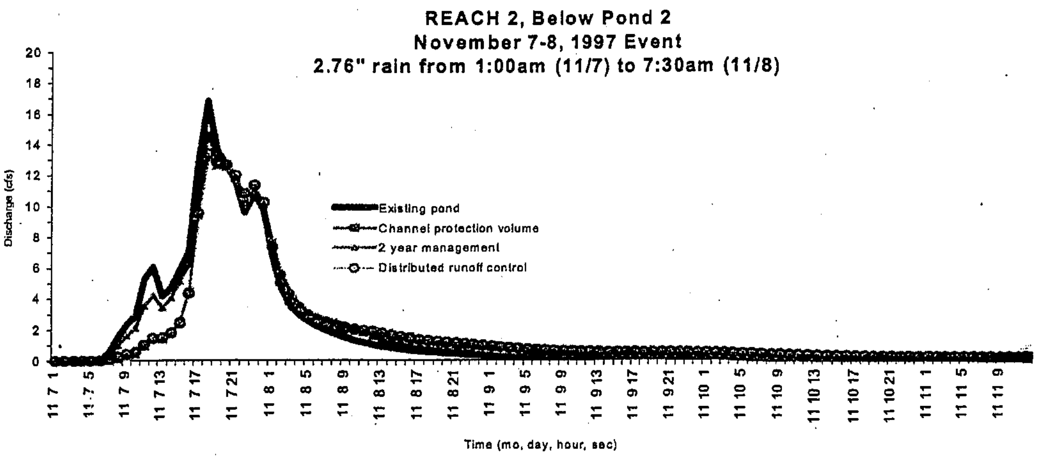


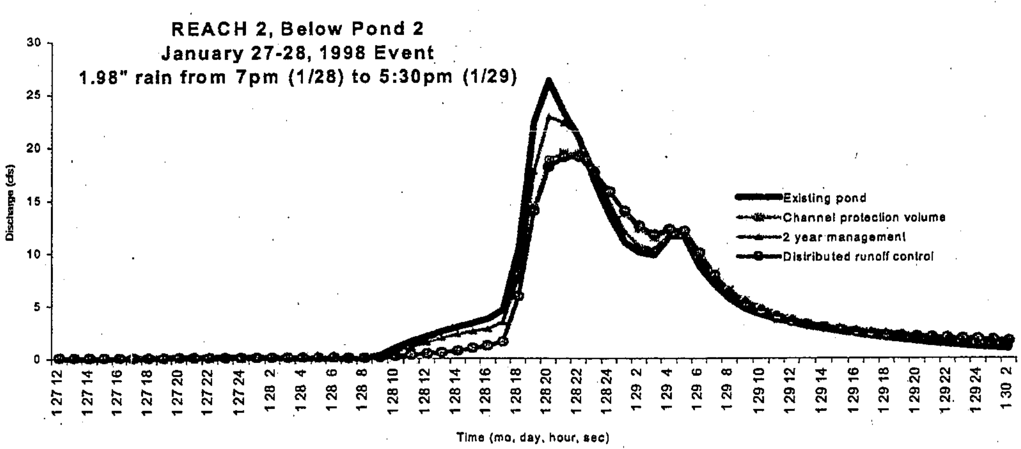



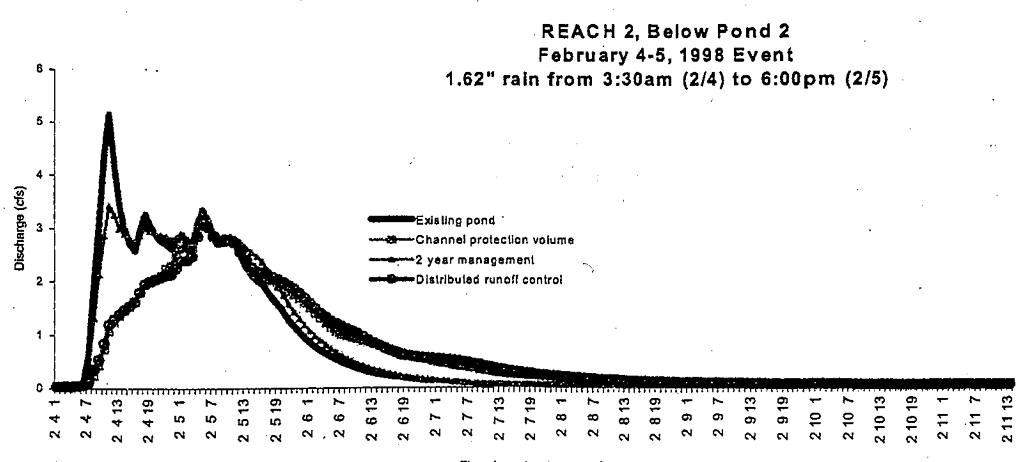

October 17-18, 1997 Event
0.96" rain from 6:30pm (10/17) to 6:30am (10/18)



## STORMWATER MANAGEMENT SCENARIOS
cont'd



## CHANNEL STABILITY ANALYSIS

The analysis of stormwater management scenarios shows that the $Cp_v$ and DRC designs provide significantly more attenuation of runoff than the 2-year design for smaller storms. The analysis also shows that $Cp_v$ and DRC provide a comparable level of management for ponds simulated in this watershed. The analysis, however, does not show the level of management necessary to protect the stream channel. This section provides an analysis of channel stability thresholds to further evaluate the effectiveness of stormwater management strategies for channel protection.

A bankfull elevation was determined for each stream reach during the assessment phase (MDE, 1999). Streams with poorly defined floodplains and incised channels, however, often make definition of the bankfull elevation a difficult field determination. The equations used in this analysis are then based on channel hydraulic geometry and do not require bankfull data.

A stage – discharge – shear stress relationship is established using WINXSPRO channel cross-section analyzer (U.S. Forest Service, 1997). Data required includes channel geometry and a Manning's *n* value assigned at various stages within the channel cross-section. These cross-section data were measured in the field and the *n* values were calculated at low stages, using observed flow and channel geometry measurements, and by applying the Manning's equation:

$$n = \frac{1.486}{(Q)(A)(R^{2/3})(S^{1/2})}$$

where Q equals discharge, A is cross-sectional area, R is the hydraulic radius and S is the channel slope. Estimates of *n* values at high flows are based on the characteristics of the channel and floodplain. Table 2 provides an example of the stage – discharge – shear stress relationship established using WINXSPRO channel cross-section analyzer.

The shear stress ratio is used as an indicator of stability at various stages (or depth) within the channel. The shear stress ratio is the ratio of the average boundary shear stress to the critical shear stress and can be defined by the equation (Johnson, et. al, 1999):

$$\tau_e = \tau_o / \tau_c$$

where $\tau_e$ = the shear stress ratio, $\tau_o$ = the average boundary shear stress, and $\tau_c$ = the critical shear stress at which grain movement is initiated. The average boundary shear stress is defined by:

$$\tau_o = \gamma RS$$

where $\gamma$ = the specific weight of water, R = the hydraulic radius, and S = channel slope. In reference to Table 2, the average boundary shear ($\tau_o$) is calculated at different depths in the channel. The WINXSPRO program can calculate hydraulic radius by using the channel cross-section data, and the cross-sectional area and wetted perimeter are computed at different depths. The critical shear stress ($\tau_c$) is then calculated using the Shields equation for critical shear stress (Johnson et. al, 1999):

$$\tau_c = \theta(\gamma_s - \gamma)D$$

where $\tau_c$ is critical shear stress, $\theta$ = Shields parameter, $\gamma_s$ = specific weight of sediment, $\gamma$ = specific weight of water, and D is particle size. The Shield's parameter is a function of particle size and the density of particle arrangement. Particle size at each cross-section was collected in the field according to the procedure in Wolman, 1954 and reported in MDE, 1999. The median size of bed materials, $D_{50}$, is used as the representative diameter (Gordon et. al, 1992).

The shear stress ratio is calculated by dividing the average boundary shear stress at a given stage by the critical shear stress. This provides a shear stress ratio at various depths within the channel cross-section. When the shear stress ratio is less than 1.0, grain motion will not occur and the channel is considered stable. From Table 2, the depth at which the shear stress ratio is greater than 1.0 can be determined.

Table 2. Stage - Discharge - Shear Stress - Shear Stress Ratio Relationship
Reach 2

| STAGE (ft) | Q (cfs) | SHEAR (psf) | SS Ratio |
|---|---|---|---|
| 0.0 | 0.00 | 0.01 | 0.02 |
| 0.1 | 0.05 | 0.06 | 0.15 |
| 0.2 | 0.47 | 0.14 | 0.34 |
| 0.3 | 1.61 | 0.25 | 0.61 |
| 0.4 | 3.61 | 0.39 | 0.95 |
| 0.5 | 6.20 | 0.53 | 1.29 |
| 0.6 | 9.39 | 0.66 | 1.61 |
| 0.7 | 13.10 | 0.78 | 1.90 |
| 0.8 | 17.33 | 0.90 | 2.20 |
| 0.9 | 22.05 | 0.82 | 2.00 |
| 1.0 | 27.43 | 0.82 | 2.00 |
| 1.1 | 33.56 | 0.89 | 2.17 |
| 1.2 | 40.43 | 0.96 | 2.34 |
| 1.3 | 48.10 | 1.06 | 2.59 |
| 1.4 | 56.33 | 1.14 | 2.78 |
| 1.5 | 63.97 | 1.23 | 3.00 |
| 1.6 | 71.84 | 1.31 | 3.20 |
| 1.7 | 81.31 | 1.38 | 3.37 |
| 1.8 | 91.60 | 1.45 | 3.54 |
| 1.9 | 103.01 | 1.57 | 3.83 |
| 2.0 | 115.03 | 1.68 | 4.10 |

A channel is considered stable in form when the shear stress is approximately 20% greater than that required to initiate motion in the center of the channel (Prestegaard et. al, 2000). This would provide a shear stress ratio ($\tau_o$ / $\tau_c$) of less than 1.2. Parker, 1979 supports this assertion indicating that stable banks can coexist with low but nonzero rates of gravel transport. This would maintain channel banks while still transporting sediment within the channel. By using a shear stress ratio of 1.2 as an indication of a stable channel, a "stable channel discharge" can be approximated by plotting the shear stress ratio versus discharge (See Figure 5). When the shear stress ratio exceeds 2.5, most of the bed is in motion, and this is considered unstable (Johnson et. al, 1999). For this analysis, a shear stress ratio less than 1.2 is the "stable channel threshold," and greater than 2.5 is the "unstable channel threshold." Shear stress ratios between 1.2 and 2.5 represent transitional phases marked by degradation or aggradation depending upon the nature and size of the sediment being supplied to the stream channel.

Using this information, the stability of discharges at various depths within the channel cross-section can be assessed. According to Figure 5, Reach 2 can receive flows up to 7 cfs while maintaining stability within the channel. Using a stable channel discharge of 7 cfs, stormwater management practices that release flows below this threshold for various size storms can be determined. Review of Figure 4 shows that the $Cp_v$ and DRC methods release less than 7 cfs for storms of 2 inches and less. While a $Cp_v$ design may cause an extended release of runoff into stream systems compared to 2 year management, as long as the release is below the stable channel threshold, the discharge will have minimal impact on the stream channel.

Comparing Figures 5 and 7 shows that the variability of stability thresholds within stream systems is dependent upon site specific channel morphology. According to Figure 7, Reach 1 is stable for flows up to 22 cfs. Therefore, the $Cp_v$ and DRC designs can protect against channel degradation during storm events greater than 2 inches of rainfall. Figures 6 and 8 show the relationship between the bankfull and stable channel discharge. Figure 6 shows the bankfull discharge is greater than the stable channel discharge for Reach 2. Therefore, Reach 2 is subject to more significant erosion within the main channel than Reach 1 (see Figure 8).

Where the bankfull elevation is lower than the top of bank, flood flows are contained within the main channel and rarely inundate the floodplain, as is the case for the channel at Reach 2. Prestegaard, 2000 states that as a result of the flood frequency regime in Maryland, high magnitude events are very probable. Therefore, flows above bankfull have a significant effect on shear stress values and therefore, channel stability. Many of Maryland's Piedmont streams are contained within narrow valleys that focus flood event energy on the main channel (Prestegaard et. al, 2000). In order to more completely evaluate the effectiveness of best management practices (BMP's) on stream channel stability, there is a need to examine flood flow conveyance within the main channel, especially in incised and confined stream channels.

Despite the shortcomings in our present understanding of BMP performance and flood conveyance, results of this study are still useful. Results show that the $Cp_v$ and DRC methods provide a comparable level of management for the ponds in this watershed. Both designs will protect stream channels for frequent storm events of less than 2.0 inches of rainfall over roughly a 24 hour period. The different stability thresholds calculated for Reaches 1 and 2 indicate that stream channels are highly variable with respect to hydrologic and morphologic stability thresholds. A site specific stream morphological study will allow for a more complete evaluation of the effectiveness of stormwater management designs for stream channel protection. The next section will summarizes data needs and methods for this level of analysis.

**Figure 5. Channel Stability Analysis**

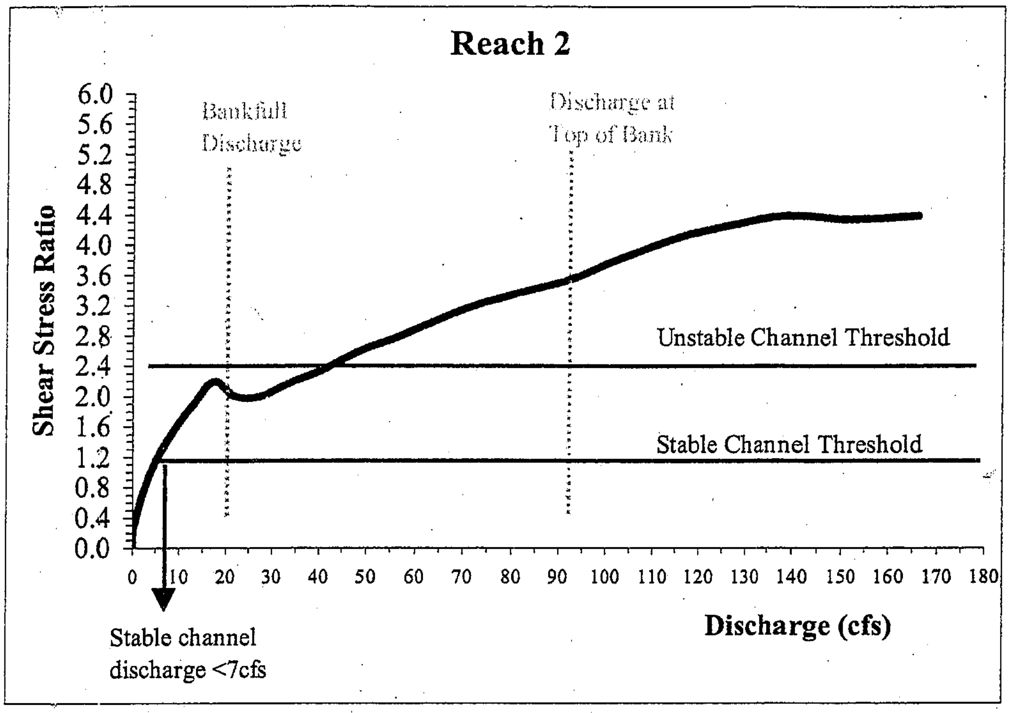



**Figure 6. Channel Cross-section at Reach 2, Below Pond 2**

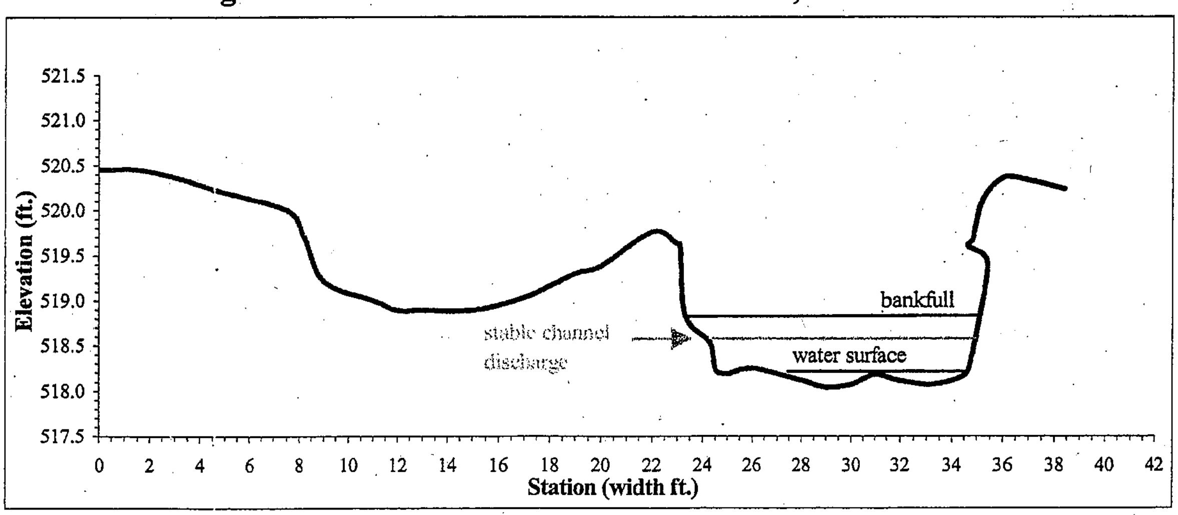


**Figure 7. Channel Stability Analysis**

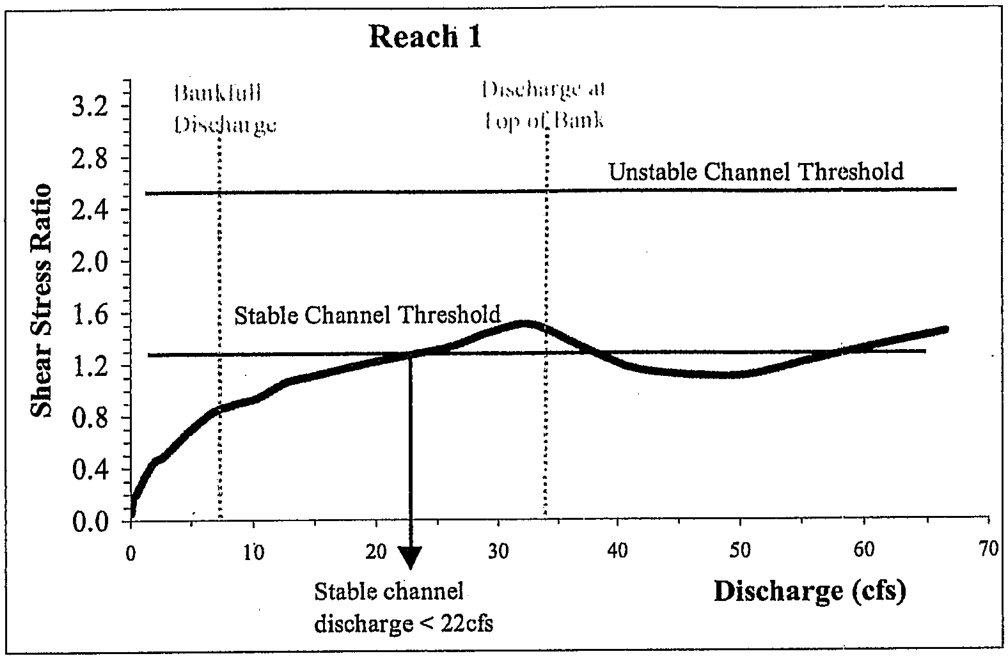
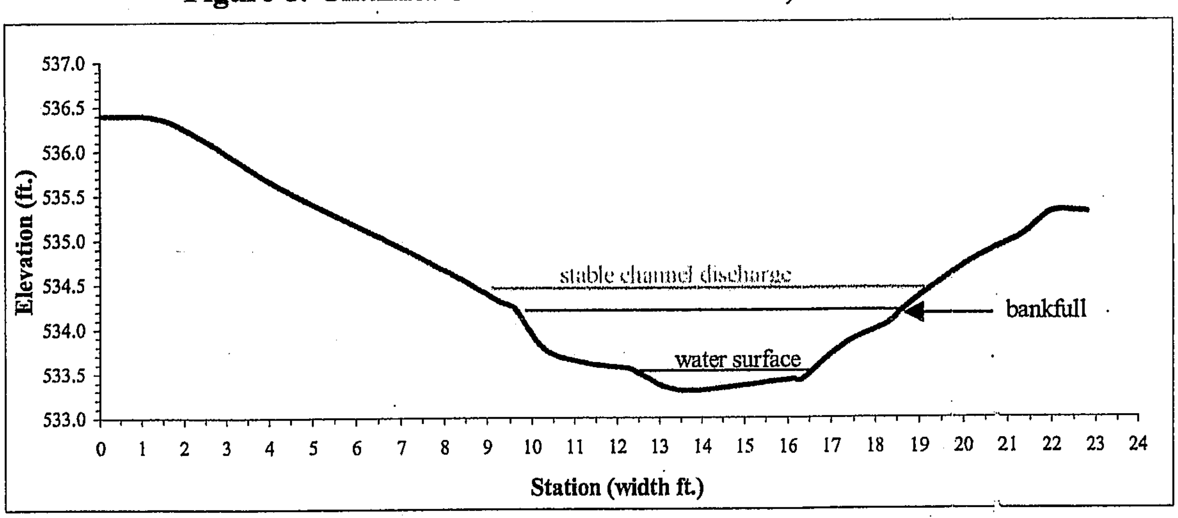



**Figure 8. Channel Cross-section at Reach 1, Below Pond 1**



## GUIDELINES FOR EVALUATING STORMWATER MANAGEMENT DESIGNS FOR STREAM CHANNEL PROTECTION

This section discusses methods and data needs for evaluating the effectiveness of existing stormwater management facilities for stream channel protection. The following protocol is intended as a starting point for analysis, however, as more data becomes available, field techniques and methodologies may be revised. The major steps that follow include:

1. Assess stream geomorphic conditions and identify stability thresholds.
2. Determine the relationship between stability thresholds, bankfull, top of bank, floodplain and design storm discharges.
3. Compare stability thresholds with the release rate for the design storm of the facility.

Stream Channel Geomorphic Assessment

- Conduct a stream stability analysis (Pfankuch, 1975 or Johnson et. al, 1999) to determine various factors influencing channel stability.
- Measure channel cross-sections, water surface gradients and particle size distribution (Rosgen, 1996, Harrelson, et. al, 1994 and Wolman, 1954).
- Survey several cross-sections along a stream reach to obtain reach – averaged values of stream width, depth, area, grain size, gradient and shear stress (Harrelson, et. al, 1994). The bankfull and floodplain elevations are identified with respect to channel geometry.
- Establish channel geometry relationships using WINXSPRO or other channel cross-section analyzer. These relationships must be consistent with observed flow measurements and field verified channel hydraulic characteristics.
- Calculate critical shear stress (Shields equation), and a shear stress ratio at variable depths along the channel cross-section. Establish a discharge - shear stress ratio relationship.
- Determine stability thresholds by determining the flows which exceed a shear stress ratio of 1.2. Determine a "stable channel discharge" and associated channel stage.
- Compare the "stable channel discharge" with results from other equations which describe critical thresholds (Bathurst, 1987 and Olsen et. al, 1997): $q_c = 0.15g^{0.5} (D_{50})^{1.5} S^{-1.12}$

Stormwater Management Modeling

- Calibrate stormwater management models in small watersheds with continuous in-stream flow measurements. USGS gaging stations may be available for larger watersheds.
- Assumptions in the model after calibration should be representative of field conditions. Data requirements using HSPF are more intensive and require real time precipitation data (hourly) for the period of model development. TR-20 data requirements are more reasonable for small watersheds, however, hourly precipitation data is useful for model calibration.
- Determine the design storm that produces peak flows that exceed the stable channel discharge.
- Compare design release rates of the stormwater management facility to stable channel discharge and other channel features.

## CONCLUSION

The overall goal for this project is to propose technical criteria for evaluating stormwater management designs and determine their effectiveness at protecting stream systems. Guidelines for evaluating stormwater management designs for stream channel protection are presented in an effort to promote further research in this area. These guidelines may be applied to other watersheds in Maryland, so that a more complete understanding of the affects of stormwater management practices on receiving stream channels may be achieved. Results from this study show that stability thresholds may be highly variable due to a range of morphologic and hydrologic conditions. Further data is also needed to evaluate the application of reach - averaged morphological data for determining channel stability thresholds. In addition research examining the affect of flood conveyance within incised stream channels is needed. This is particularly a concern in Maryland's Piedmont, where stream channels are often confined within narrow valleys. This will help identify further needs and expand on existing knowledge in the area of stormwater management for protecting stream channels.

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**Appendix A**

Hydraulic Function Tables (F-TABLES)

Existing Ponds
F-TABLES

Reach 1, Below Pond 1

| depth (ft) | area (acres) | volume (acre-ft) | outflow (ft3/s) |
|---|---|---|---|
| 0.0 | 0.0 | 0.0 | 0.0 |
| 0.1 | 1.9 | 0.2 | 4.9 |
| 0.2 | 1.9 | 0.4 | 9.8 |
| 0.3 | 1.9 | 0.6 | 14.7 |
| 0.4 | 1.9 | 0.8 | 19.6 |
| 0.5 | 1.9 | 0.9 | 24.4 |
| 0.6 | 1.9 | 1.1 | 29.3 |
| 0.7 | 1.9 | 1.3 | 34.2 |
| 0.8 | 1.9 | 1.5 | 39.1 |
| 0.9 | 1.9 | 1.7 | 44.0 |
| 1.0 | 1.9 | 1.9 | 48.7 |
| 1.1 | 1.9 | 2.1 | 53.0 |
| 1.2 | 1.9 | 2.3 | 57.9 |
| 1.3 | 1.9 | 2.5 | 62.8 |
| 1.4 | 2.0 | 2.7 | 67.7 |
| 1.5 | 2.0 | 2.9 | 70.2 |
| 1.6 | 2.0 | 3.2 | 75.8 |
| 1.7 | 2.0 | 3.4 | 81.4 |
| 1.8 | 2.0 | 3.6 | 87.0 |
| 1.9 | 2.0 | 3.8 | 92.7 |
| 2.0 | 2.0 | 4.0 | 98.2 |

Reach 2, Below Pond 2

| depth (ft) | area (acres) | volume (acre-ft) | outflow (ft3/s) |
|---|---|---|---|
| 0.0 | 0.0 | 0.0 | 0.0 |
| 0.2 | 4.0 | 0.8 | 4.2 |
| 0.3 | 4.0 | 1.2 | 7.2 |
| 0.4 | 4.0 | 1.6 | 9.6 |
| 0.5 | 4.0 | 2.0 | 12.1 |
| 0.6 | 4.0 | 2.4 | 16.5 |
| 0.7 | 4.1 | 2.9 | 21.0 |
| 0.8 | 4.1 | 3.3 | 25.4 |
| 0.9 | 4.2 | 3.8 | 29.8 |
| 1.0 | 4.2 | 4.2 | 34.1 |
| 1.2 | 5.1 | 6.1 | 37.3 |
| 1.4 | 5.7 | 8.0 | 40.5 |
| 1.6 | 6.1 | 9.7 | 42.3 |
| 1.8 | 6.1 | 11.0 | 42.5 |
| 2.0 | 6.1 | 12.3 | 42.8 |
| 2.2 | 6.2 | 13.6 | 51.4 |
| 2.4 | 6.2 | 14.9 | 60.0 |
| 2.6 | 6.2 | 16.2 | 72.4 |
| 2.8 | 6.2 | 17.5 | 88.6 |
| 3.0 | 6.3 | 18.8 | 105.0 |
| 3.2 | 6.3 | 20.1 | 130.8 |
| 3.4 | 6.3 | 21.4 | 156.6 |
| 3.6 | 6.4 | 23.2 | 185.6 |
| 3.8 | 6.7 | 25.6 | 217.8 |
| 4.0 | 7.0 | 28.0 | 250.0 |

Reach 3

| depth (ft) | area (acres) | volume (acre-ft) | outflow (ft3/s) |
|---|---|---|---|
| 0.0 | 0.4 | 0.0 | 0.0 |
| 0.2 | 0.4 | 0.1 | 1.4 |
| 2.2 | 0.6 | 1.1 | 69.6 |
| 2.6 | 0.7 | 1.4 | 94.7 |
| 6.3 | 19.3 | 57.1 | 5788.0 |
| 10.0 | 27.8 | 144.4 | 21310.0 |
| 12.5 | 31.1 | 218.0 | 39360.0 |
| 15.0 | 34.3 | 299.8 | 62630.0 |

Reach 4

| depth (ft) | area (acres) | volume (acre-ft) | outflow (ft3/s) |
|---|---|---|---|
| 0.0 | 0.3 | 0.0 | 0.0 |
| 0.2 | 0.3 | 0.1 | 1.2 |
| 2.0 | 0.5 | 0.8 | 60.0 |
| 2.8 | 0.6 | 1.3 | 114.9 |
| 5.9 | 18.2 | 45.7 | 5523.0 |
| 9.0 | 25.8 | 114.0 | 20030.0 |
| 11.5 | 29.3 | 182.9 | 40520.0 |
| 14.0 | 32.8 | 260.6 | 67820.0 |

Reach 5

| depth (ft) | area (acres) | volume (acre-ft) | outflow (ft3/s) |
|---|---|---|---|
| 0.0 | 2.0 | 0.0 | 0.0 |
| 0.2 | 2.1 | 0.5 | 11.1 |
| 2.4 | 2.5 | 5.4 | 512.6 |
| 3.5 | 2.8 | 8.4 | 981.9 |
| 5.3 | 43.4 | 71.5 | 5961.0 |
| 7.0 | 57.9 | 160.1 | 18860.0 |
| 9.5 | 67.5 | 316.9 | 53180.0 |
| 12.0 | 77.0 | 497.6 | 103300.0 |

2 year management
FTABLES

Reach 1, Below Pond 1

| depth (ft) | area (acres) | volume (acre-ft) | outflow (ft3/s) |
|---|---|---|---|
| 0.0 | 0.0 | 0.0 | 0.0 |
| 0.1 | 1.9 | 0.2 | 1.0 |
| 0.2 | 1.9 | 0.4 | 2.1 |
| 0.3 | 1.9 | 0.6 | 4.0 |
| 0.4 | 1.9 | 0.8 | 6.0 |
| 0.5 | 1.9 | 0.9 | 9.1 |
| 0.6 | 1.9 | 1.1 | 13.1 |
| 0.7 | 1.9 | 1.3 | 17.7 |
| 0.8 | 1.9 | 1.5 | 22.9 |
| 0.9 | 1.9 | 1.7 | 28.5 |
| 1.0 | 1.9 | 1.9 | 34.6 |
| 1.1 | 1.9 | 2.1 | 39.7 |
| 1.2 | 1.9 | 2.3 | 44.8 |
| 1.3 | 1.9 | 2.5 | 49.8 |
| 1.4 | 2.0 | 2.7 | 54.9 |
| 1.5 | 2.0 | 2.9 | 60.0 |
| 1.6 | 2.0 | 3.2 | 66.0 |
| 1.7 | 2.0 | 3.4 | 72.0 |
| 1.8 | 2.0 | 3.6 | 78.0 |
| 1.9 | 2.0 | 3.8 | 84.0 |
| 2.0 | 2.0 | 4.0 | 90.0 |

Reach 2, Below Pond 2

| depth (ft) | area (acres) | volume (acre-ft) | outflow (ft3/s) |
|---|---|---|---|
| 0.0 | 0.0 | 0.0 | 0.0 |
| 0.2 | 4.0 | 0.8 | 2.4 |
| 0.3 | 4.0 | 1.2 | 3.0 |
| 0.4 | 4.0 | 1.6 | 4.8 |
| 0.5 | 4.0 | 2.0 | 6.6 |
| 0.6 | 4.0 | 2.4 | 8.8 |
| 0.7 | 4.1 | 2.9 | 11.0 |
| 0.8 | 4.1 | 3.3 | 13.8 |
| 0.9 | 4.2 | 3.8 | 17.2 |
| 1.0 | 4.2 | 4.2 | 20.9 |
| 1.2 | 5.1 | 6.1 | 29.4 |
| 1.4 | 5.7 | 8.0 | 37.9 |
| 1.6 | 6.1 | 9.7 | 42.9 |
| 1.8 | 6.1 | 11.0 | 43.1 |
| 2.0 | 6.1 | 12.3 | 44.0 |
| 2.2 | 6.2 | 13.6 | 53.2 |
| 2.4 | 6.2 | 14.9 | 62.4 |
| 2.6 | 6.2 | 16.2 | 83.2 |
| 2.8 | 6.2 | 17.5 | 99.4 |
| 3.0 | 6.3 | 18.8 | 107.5 |
| 3.2 | 6.3 | 20.1 | 133.3 |
| 3.4 | 6.3 | 21.4 | 159.1 |
| 3.6 | 6.4 | 23.2 | 204.4 |
| 3.8 | 6.7 | 25.6 | 236.8 |
| 4.0 | 7.0 | 28.0 | 253.0 |

Reach 3

| depth (ft) | area (acres) | volume (acre-ft) | outflow (ft3/s) |
|---|---|---|---|
| 0.0 | 0.4 | 0.0 | 0.0 |
| 0.2 | 0.4 | 0.1 | 1.4 |
| 2.2 | 0.6 | 1.1 | 69.6 |
| 2.6 | 0.7 | 1.4 | 94.7 |
| 6.3 | 19.3 | 57.1 | 5788.0 |
| 10.0 | 27.8 | 144.4 | 21310.0 |
| 12.5 | 31.1 | 218.0 | 39360.0 |
| 15.0 | 34.3 | 299.8 | 62630.0 |

Reach 4

| depth (ft) | area (acres) | volume (acre-ft) | outflow (ft3/s) |
|---|---|---|---|
| 0.0 | 0.3 | 0.0 | 0.0 |
| 0.2 | 0.3 | 0.1 | 1.2 |
| 2.0 | 0.5 | 0.8 | 60.0 |
| 2.8 | 0.6 | 1.3 | 114.9 |
| 5.9 | 18.2 | 45.7 | 5523.0 |
| 9.0 | 25.8 | 114.0 | 20030.0 |
| 11.5 | 29.3 | 182.9 | 40520.0 |
| 14.0 | 32.8 | 260.6 | 67820.0 |

Reach 5

| depth (ft) | area (acres) | volume (acre-ft) | outflow (ft3/s) |
|---|---|---|---|
| 0.0 | 2.0 | 0.0 | 0.0 |
| 0.2 | 2.1 | 0.5 | 11.1 |
| 2.4 | 2.5 | 5.4 | 512.6 |
| 3.5 | 2.8 | 8.4 | 981.9 |
| 5.3 | 43.4 | 71.5 | 5961.0 |
| 7.0 | 57.9 | 160.1 | 18860.0 |
| 9.5 | 67.5 | 316.9 | 53180.0 |
| 12.0 | 77.0 | 497.6 | 103300.0 |

Extended Detention
FTABLES

Reach 1, Below Pond 1

| depth (ft) | area (acres) | volume (acre-ft) | outflow (ft3/s) |
|---|---|---|---|
| 0.0 | 0.0 | 0.0 | 0.0 |
| 0.1 | 1.9 | 0.2 | 0.1 |
| 0.2 | 1.9 | 0.4 | 0.3 |
| 0.3 | 1.9 | 0.6 | 0.5 |
| 0.4 | 1.9 | 0.8 | 0.7 |
| 0.5 | 1.9 | 0.9 | 1.0 |
| 0.6 | 1.9 | 1.1 | 2.8 |
| 0.7 | 1.9 | 1.3 | 5.8 |
| 0.8 | 1.9 | 1.5 | 9.5 |
| 0.9 | 1.9 | 1.7 | 14.0 |
| 1.0 | 1.9 | 1.9 | 18.9 |
| 1.1 | 1.9 | 2.1 | 28.5 |
| 1.2 | 1.9 | 2.3 | 38.1 |
| 1.3 | 1.9 | 2.5 | 47.8 |
| 1.4 | 2.0 | 2.7 | 57.4 |
| 1.5 | 2.0 | 2.9 | 67.0 |
| 1.6 | 2.0 | 3.2 | 71.6 |
| 1.7 | 2.0 | 3.4 | 76.2 |
| 1.8 | 2.0 | 3.6 | 80.8 |
| 1.9 | 2.0 | 3.8 | 85.4 |
| 2.0 | 2.0 | 4.0 | 90.0 |

Reach 2, Below Pond 2

| depth (ft) | area (acres) | volume (acre-ft) | outflow (ft3/s) |
|---|---|---|---|
| 0.0 | 0.0 | 0.0 | 0.0 |
| 0.2 | 4.0 | 0.8 | 0.3 |
| 0.3 | 4.0 | 1.2 | 0.5 |
| 0.4 | 4.0 | 1.6 | 0.8 |
| 0.5 | 4.0 | 2.0 | 1.0 |
| 0.6 | 4.0 | 2.4 | 1.6 |
| 0.7 | 4.1 | 2.9 | 2.1 |
| 0.8 | 4.1 | 3.3 | 3.7 |
| 0.9 | 4.2 | 3.8 | 6.3 |
| 1.0 | 4.2 | 4.2 | 8.8 |
| 1.2 | 5.1 | 6.1 | 16.9 |
| 1.4 | 5.7 | 8.0 | 25.0 |
| 1.6 | 6.1 | 9.7 | 32.0 |
| 1.8 | 6.1 | 11.0 | 38.0 |
| 2.0 | 6.1 | 12.3 | 44.0 |
| 2.2 | 6.2 | 13.6 | 53.2 |
| 2.4 | 6.2 | 14.9 | 62.4 |
| 2.6 | 6.2 | 16.2 | 75.0 |
| 2.8 | 6.2 | 17.5 | 91.3 |
| 3.0 | 6.3 | 18.8 | 107.5 |
| 3.2 | 6.3 | 20.1 | 133.3 |
| 3.4 | 6.3 | 21.4 | 159.1 |
| 3.6 | 6.4 | 23.2 | 188.2 |
| 3.8 | 6.7 | 25.6 | 220.6 |
| 4.0 | 7.0 | 28.0 | 253.0 |

Reach 3

| depth (ft) | area (acres) | volume (acre-ft) | outflow (ft3/s) |
|---|---|---|---|
| 0.0 | 0.4 | 0.0 | 0.0 |
| 0.2 | 0.4 | 0.1 | 1.4 |
| 2.2 | 0.6 | 1.1 | 69.6 |
| 2.6 | 0.7 | 1.4 | 94.7 |
| 6.3 | 19.3 | 57.1 | 5788.0 |
| 10.0 | 27.8 | 144.4 | 21310.0 |
| 12.5 | 31.1 | 218.0 | 39360.0 |
| 15.0 | 34.3 | 299.8 | 62630.0 |

Reach 4

| depth (ft) | area (acres) | volume (acre-ft) | outflow (ft3/s) |
|---|---|---|---|
| 0.0 | 0.3 | 0.0 | 0.0 |
| 0.2 | 0.3 | 0.1 | 1.2 |
| 2.0 | 0.5 | 0.8 | 60.0 |
| 2.8 | 0.6 | 1.3 | 114.9 |
| 5.9 | 18.2 | 45.7 | 5523.0 |
| 9.0 | 25.8 | 114.0 | 20030.0 |
| 11.5 | 29.3 | 182.9 | 40520.0 |
| 14.0 | 32.8 | 260.6 | 67820.0 |

Reach 5

| depth (ft) | area (acres) | volume (acre-ft) | outflow (ft3/s) |
|---|---|---|---|
| 0.0 | 2.0 | 0.0 | 0.0 |
| 0.2 | 2.1 | 0.5 | 11.1 |
| 2.4 | 2.5 | 5.4 | 512.6 |
| 3.5 | 2.8 | 8.4 | 981.9 |
| 5.3 | 43.4 | 71.5 | 5961.0 |
| 7.0 | 57.9 | 160.1 | 18860.0 |
| 9.5 | 67.5 | 316.9 | 53180.0 |
| 12.0 | 77.0 | 497.6 | 103300.0 |

Distributed Runoff Control
FTABLES

Reach 1, Below Pond 1

| depth (ft) | area (acres) | volume (acre-ft) | outflow (ft3/s) |
|---|---|---|---|
| 0.0 | 0.0 | 0.0 | 0.0 |
| 0.1 | 1.9 | 0.2 | 0.2 |
| 0.2 | 1.9 | 0.4 | 0.4 |
| 0.3 | 1.9 | 0.6 | 0.8 |
| 0.4 | 1.9 | 0.8 | 1.2 |
| 0.5 | 1.9 | 0.9 | 1.8 |
| 0.6 | 1.9 | 1.1 | 2.6 |
| 0.7 | 1.9 | 1.3 | 3.6 |
| 0.8 | 1.9 | 1.5 | 4.6 |
| 0.9 | 1.9 | 1.7 | 15.0 |
| 1.0 | 1.9 | 1.9 | 25.0 |
| 1.1 | 1.9 | 2.1 | 35.0 |
| 1.2 | 1.9 | 2.3 | 45.0 |
| 1.3 | 1.9 | 2.5 | 50.0 |
| 1.4 | 2.0 | 2.7 | 55.0 |
| 1.5 | 2.0 | 2.9 | 60.0 |
| 1.6 | 2.0 | 3.2 | 66.0 |
| 1.7 | 2.0 | 3.4 | 72.0 |
| 1.8 | 2.0 | 3.6 | 78.0 |
| 1.9 | 2.0 | 3.8 | 84.0 |
| 2.0 | 2.0 | 4.0 | 90.0 |

Reach 2, Below Pond 2

| depth (ft) | area (acres) | volume (acre-ft) | outflow (ft3/s) |
|---|---|---|---|
| 0.0 | 0.0 | 0.0 | 0.0 |
| 0.2 | 4.0 | 0.8 | 0.5 |
| 0.3 | 4.0 | 1.2 | 0.6 |
| 0.4 | 4.0 | 1.6 | 1.0 |
| 0.5 | 4.0 | 2.0 | 1.3 |
| 0.6 | 4.0 | 2.4 | 1.8 |
| 0.7 | 4.1 | 2.9 | 2.2 |
| 0.8 | 4.1 | 3.3 | 3.7 |
| 0.9 | 4.2 | 3.8 | 7.0 |
| 1.0 | 4.2 | 4.2 | 10.0 |
| 1.2 | 5.1 | 6.1 | 17.0 |
| 1.4 | 5.7 | 8.0 | 25.5 |
| 1.6 | 6.1 | 9.7 | 32.0 |
| 1.8 | 6.1 | 11.0 | 40.0 |
| 2.0 | 6.1 | 12.3 | 47.0 |
| 2.2 | 6.2 | 13.6 | 53.0 |
| 2.4 | 6.2 | 14.9 | 59.0 |
| 2.6 | 6.2 | 16.2 | 83.0 |
| 2.8 | 6.2 | 17.5 | 99.0 |
| 3.0 | 6.3 | 18.8 | 108.0 |
| 3.2 | 6.3 | 20.1 | 133.0 |
| 3.4 | 6.3 | 21.4 | 159.0 |
| 3.6 | 6.4 | 23.2 | 204.0 |
| 3.8 | 6.7 | 25.6 | 237.0 |
| 4.0 | 7.0 | 28.0 | 253.0 |

Reach 3

| depth (ft) | area (acres) | volume (acre-ft) | outflow (ft3/s) |
|---|---|---|---|
| 0.0 | 0.4 | 0.0 | 0.0 |
| 0.2 | 0.4 | 0.1 | 1.4 |
| 2.2 | 0.6 | 1.1 | 69.6 |
| 2.6 | 0.7 | 1.4 | 94.7 |
| 6.3 | 19.3 | 57.1 | 5788.0 |
| 10.0 | 27.8 | 144.4 | 21310.0 |
| 12.5 | 31.1 | 218.0 | 39360.0 |
| 15.0 | 34.3 | 299.8 | 62630.0 |

Reach 4

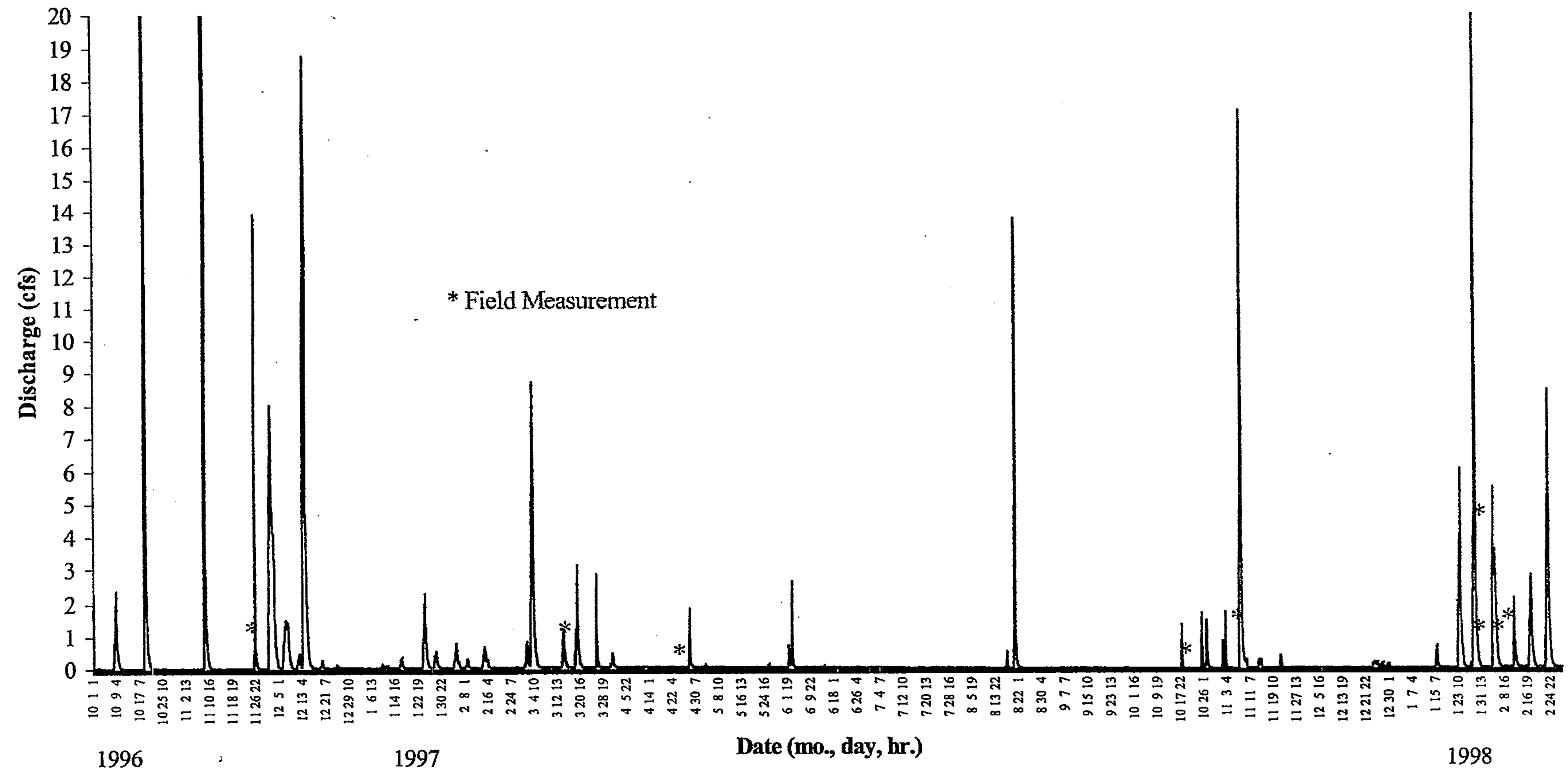
| depth (ft) | area (acres) | volume (acre-ft) | outflow (ft3/s) |
|---|---|---|---|
| 0.0 | 0.3 | 0.0 | 0.0 |
| 0.2 | 0.3 | 0.1 | 1.2 |
| 2.0 | 0.5 | 0.8 | 60.0 |
| 2.8 | 0.6 | 1.3 | 114.9 |
| 5.9 | 18.2 | 45.7 | 5523.0 |
| 9.0 | 25.8 | 114.0 | 20030.0 |
| 11.5 | 29.3 | 182.9 | 40520.0 |
| 14.0 | 32.8 | 260.6 | 67820.0 |

Reach 5

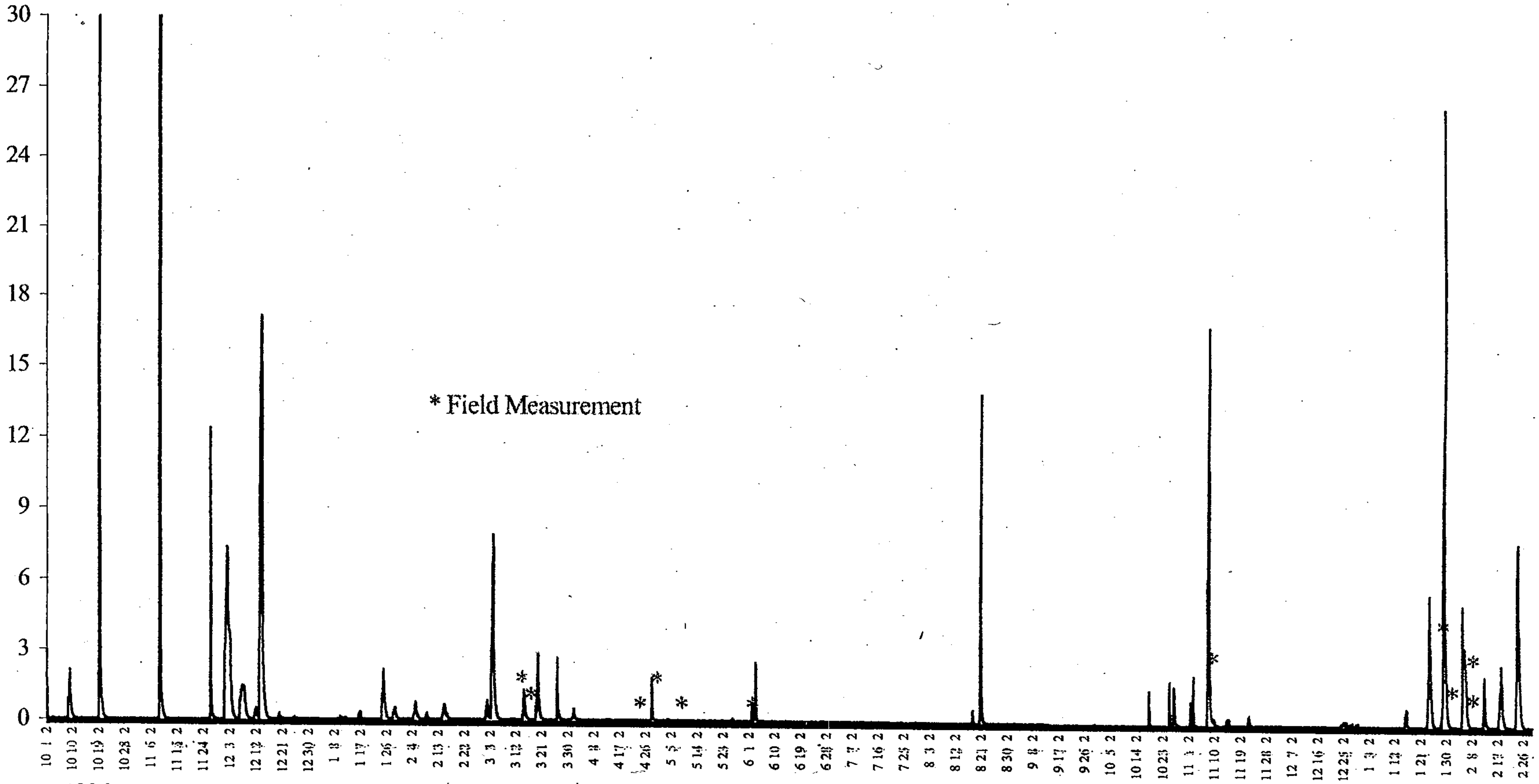
| depth (ft) | area (acres) | volume (acre-ft) | outflow (ft3/s) |
|---|---|---|---|
| 0.0 | 2.0 | 0.0 | 0.0 |
| 0.2 | 2.1 | 0.5 | 11.1 |
| 2.4 | 2.5 | 5.4 | 512.6 |
| 3.5 | 2.8 | 8.4 | 981.9 |
| 5.3 | 43.4 | 71.5 | 5961.0 |
| 7.0 | 57.9 | 160.1 | 18860.0 |
| 9.5 | 67.5 | 316.9 | 53180.0 |
| 12.0 | 77.0 | 497.6 | 103300.0 |

Appendix B

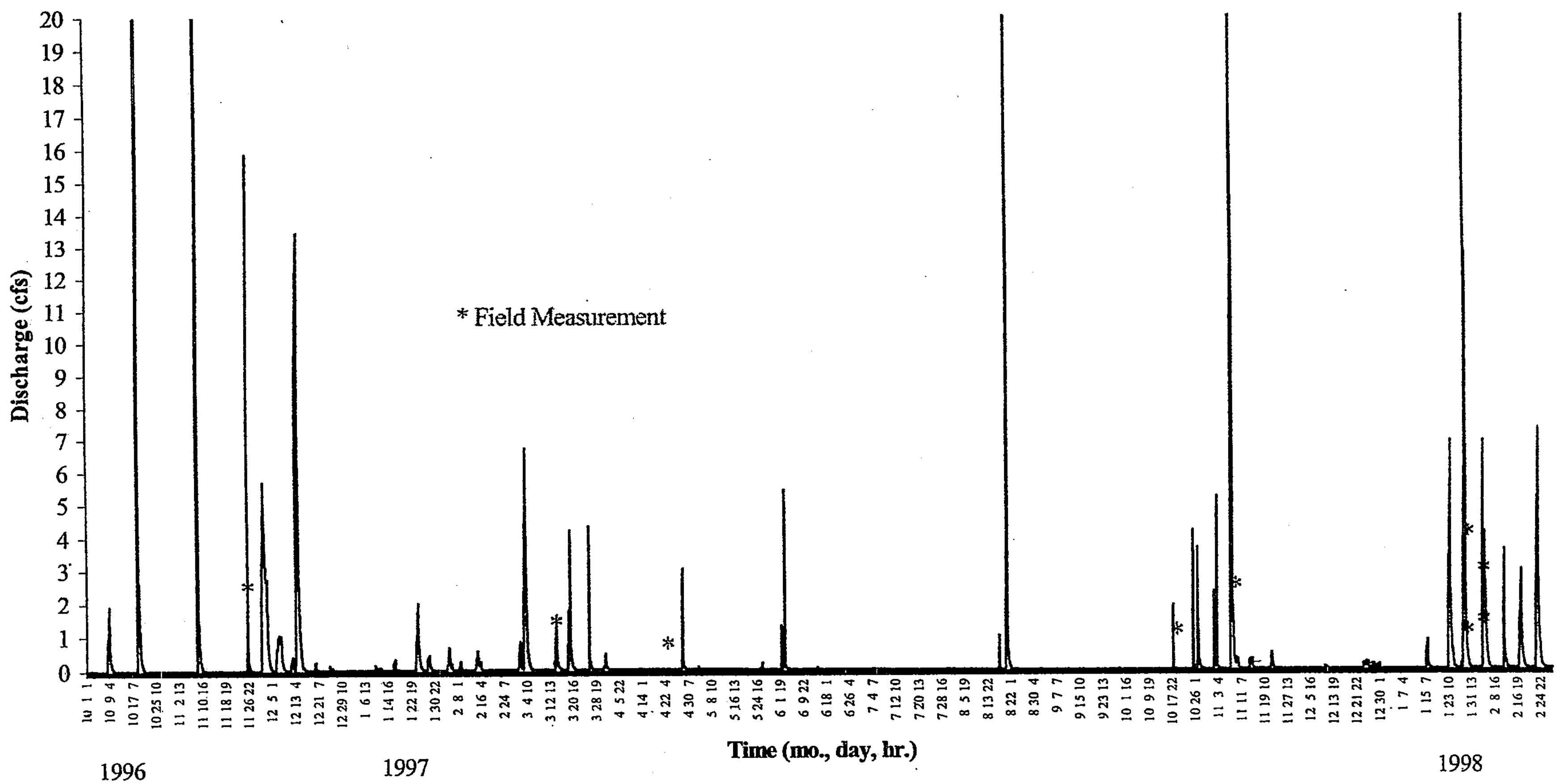
## HSPF Model Calibration
## Reach 3



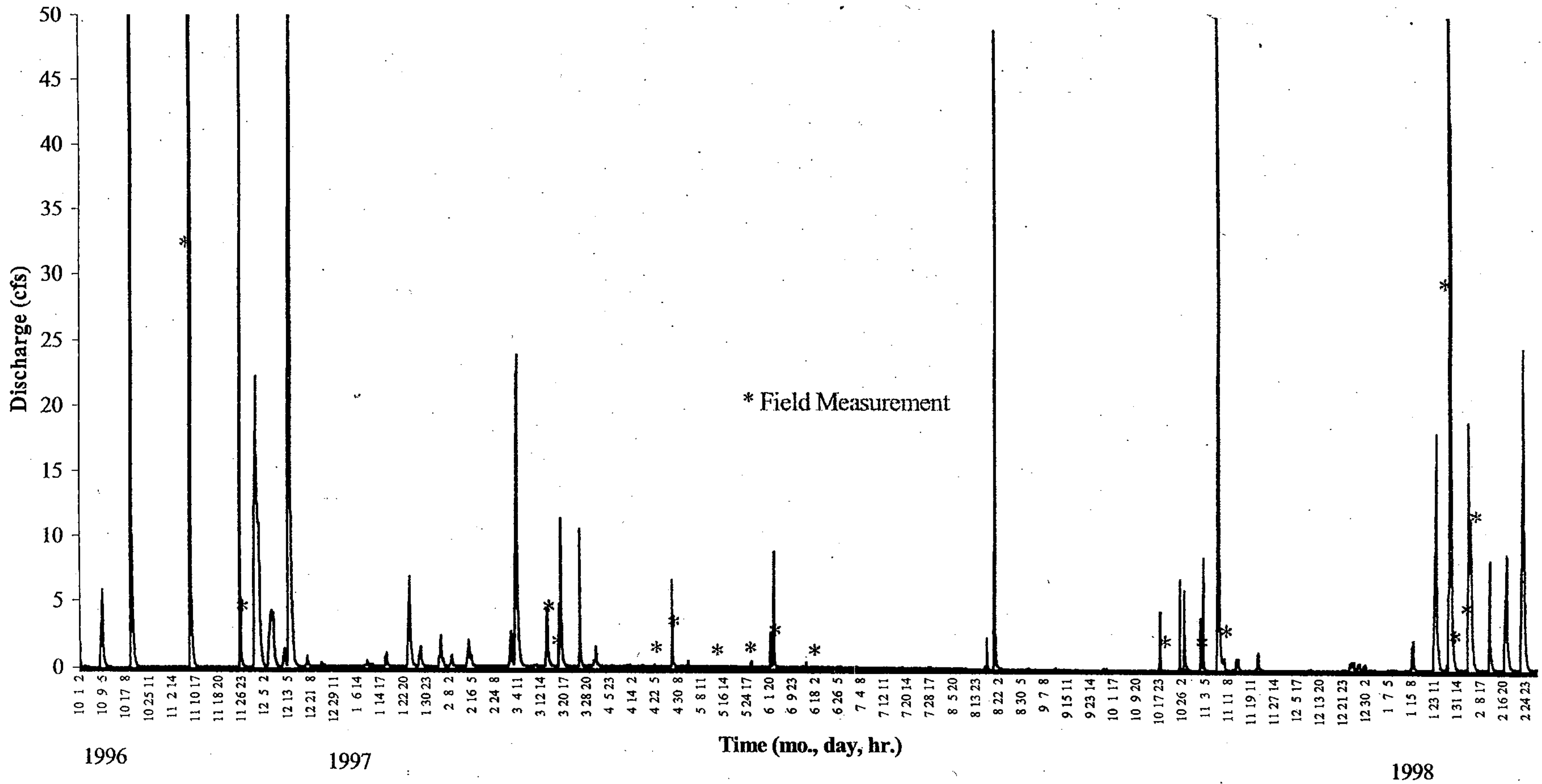
## HSPF Model Calibration
## Reach 2, Below Pond 2



# HSPF Model Calibration
## Reach 4



## HSPF Model Calibration
## Reach 5



# Appendix C

## Sensitivity Analysis

**Sensitivity Analysis:** This table shows the range of variation of model output for those parameters found to affect the model most significantly. The significant differences shown within the typical values range, indicate the importance of obtaining careful estimates in order to accurately represent the conditions within the watershed.

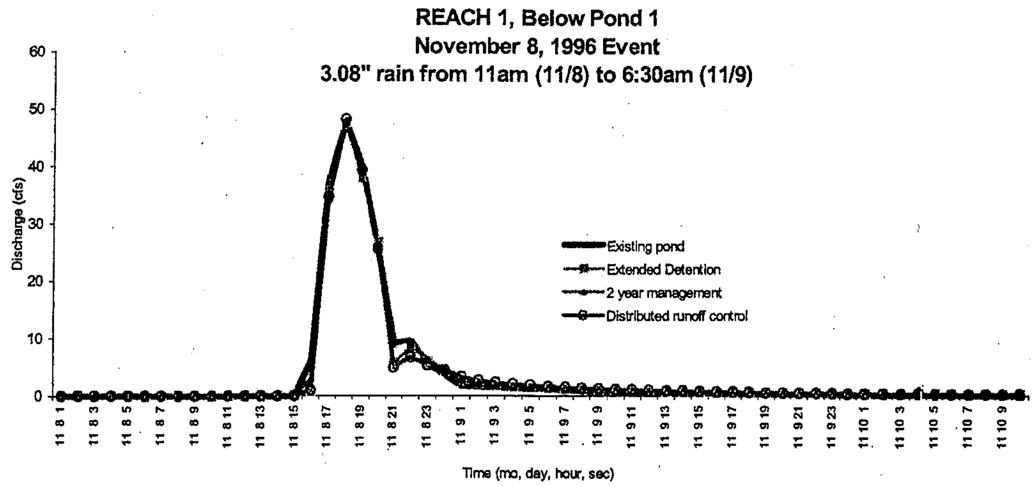
| Parameter | Typical Values[1] | Range of changes From To | Percent Difference in model output |
|---|---|---|---|
| **INFILT** Soil Infiltration rate | **01 - 0.25** | **0.01 to 0.25** | **10** |
| | | 0.01 to 1.00 | 30 |
| | | 0.01 to 20.0 | 35 |
| **AGWRC** Groundwater recession rate | **0.92 - 0.99** | **0.99 to 0.92** | **60** |
| | | 0.99 to 0.90 | 63 |
| | | 0.99 to 0.80 | 73 |
| | | 0.99 to 0.60 | 80 |
| | | 0.99 to 0.30 | 87 |
| | | 0.99 to 0.01 | 91 |
| **DEEPFR** Fraction of infiltrating water lost to deep aquifers | **0 - 0.2** | 0.0 to 0.05 | 5 |
| | | 0.0 to 0.1 | 10 |
| | | **0.0 to 0.2** | **24** |
| | | 0.0 to 0.4 | 63 |
| **LZSN** Lower Zone Nominal Soil Moisture Storage | **3.0 - 8.0** | **3 to 8.00** | **19** |
| | | 3 to 12.0 | 30 |
| **KVARY** Groundwater recession flow | **3.0** | 0.0 to 1.0 | 5 |
| | | **0.0 to 3.0** | **12** |
| | | 0.0 to 6.0 | 14 |
| **BASETP** Evapotrans by riparian vegetation | **0 - 0.05** | **0 to 0.05** | **1** |
| | | 0 to 0.20 | 4 |
| | | 0 to 1.00 | 9 |
| **LZETP** Index to lower zone evapotrans | **0.2 - 0.7** | **0.2 to 0.7** | **27** |
| | | 0.2 to 0.4 | 15 |
| | | 0.1 to 0.2 | 8 |

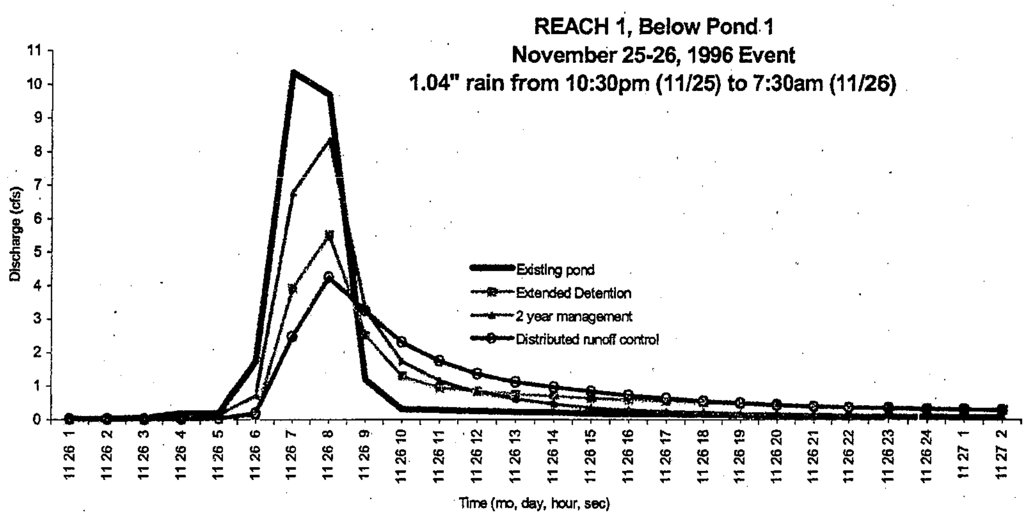
1. U.S. Environmental Protection Agency. 1999c. BASINS Technical Note 6. Estimating Hydrology Parameters for NPSM/HSPF. U.S. EPA. Office of Water. EPA-823-R-99-005

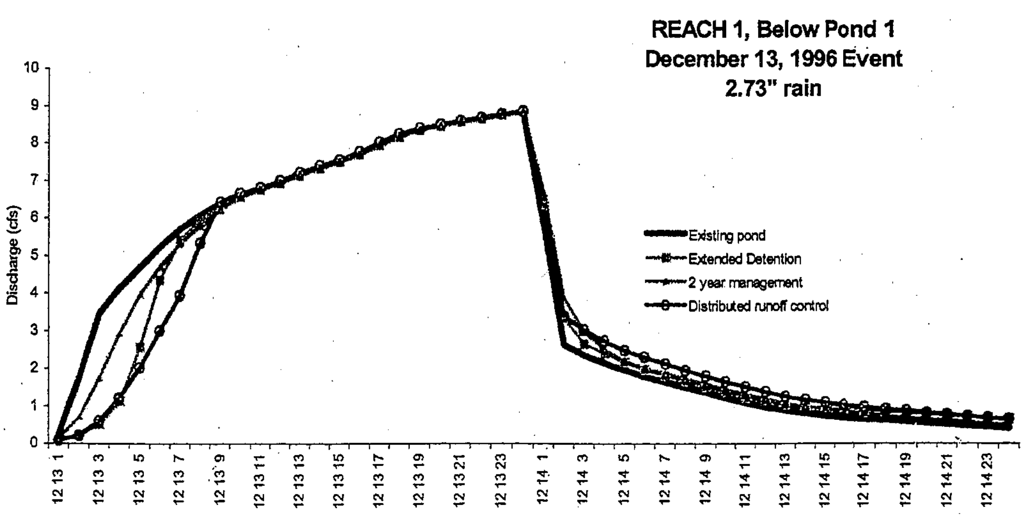
# Appendix D

## Stormwater Management Scenarios

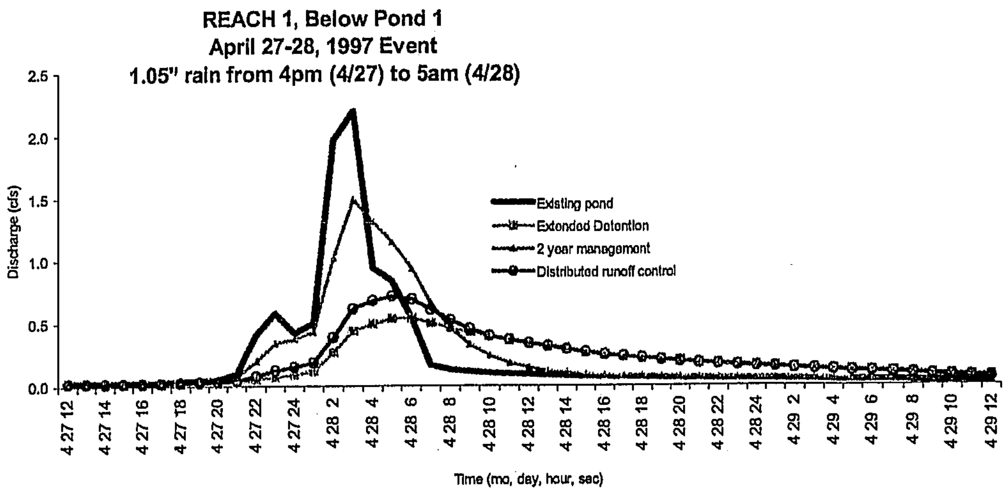
## STORMWATER MANAGEMENT SCENARIOS

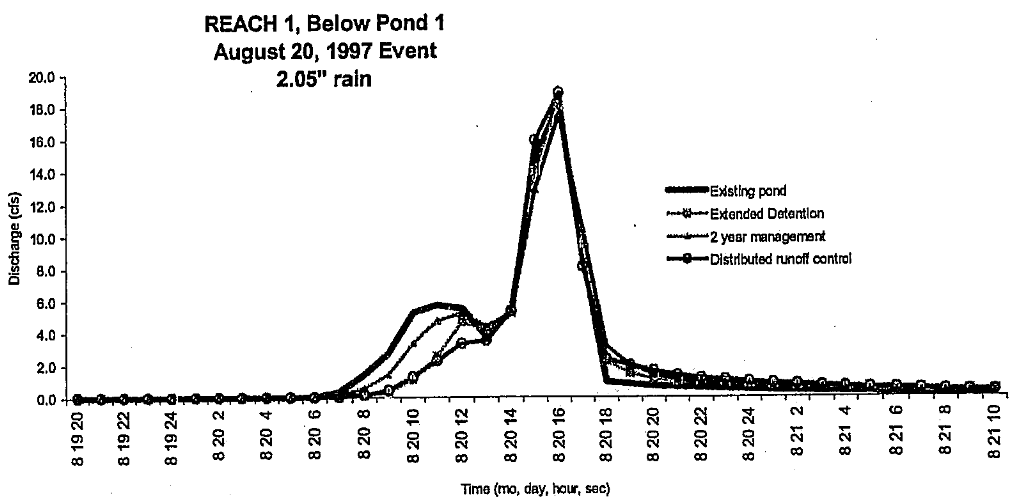


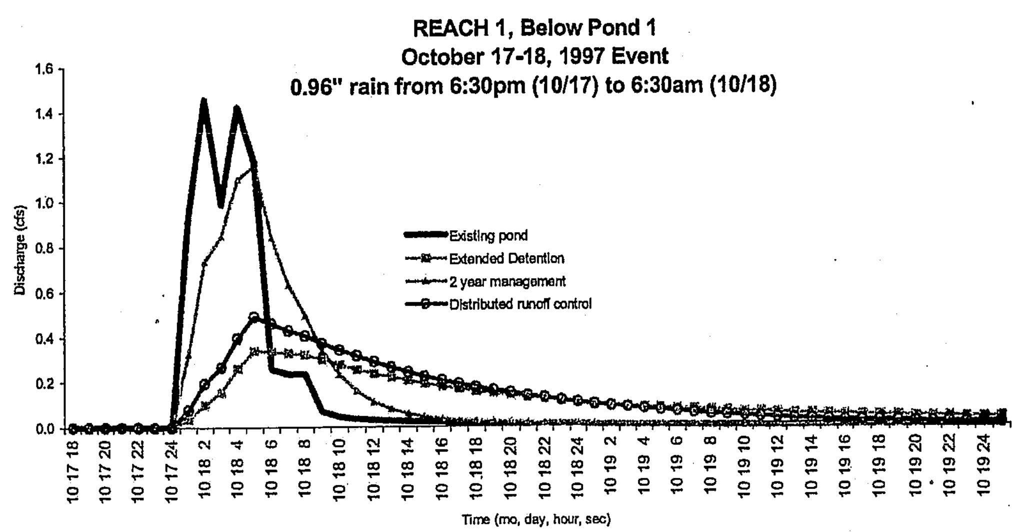



## STORMWATER MANAGEMENT SCENARIOS
cont'd

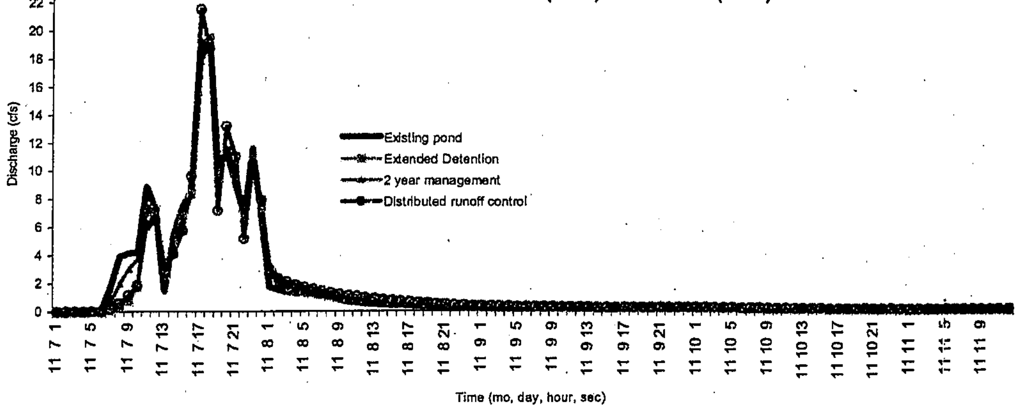


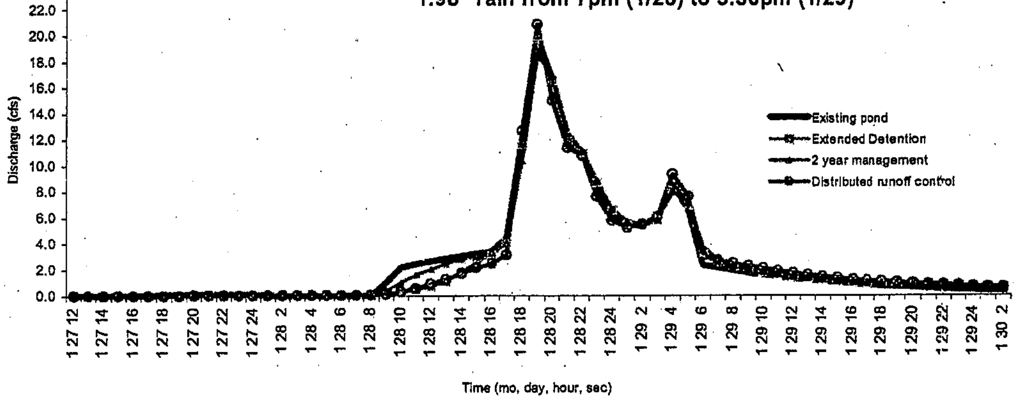



## STORMWATER MANAGEMENT SCENARIOS
cont'd

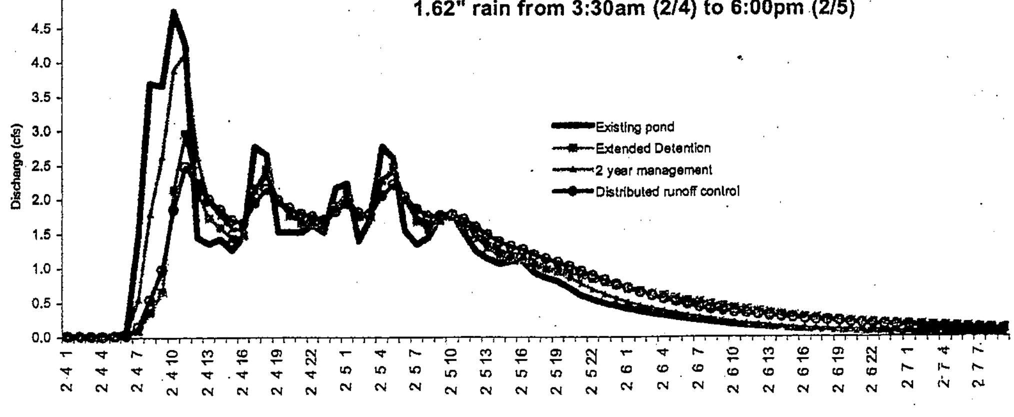
### REACH 1, Below Pond 1
**November 7-8, 1997 Event**
**2.76" rain from 1:00am (11/7) to 7:30am (11/8)**



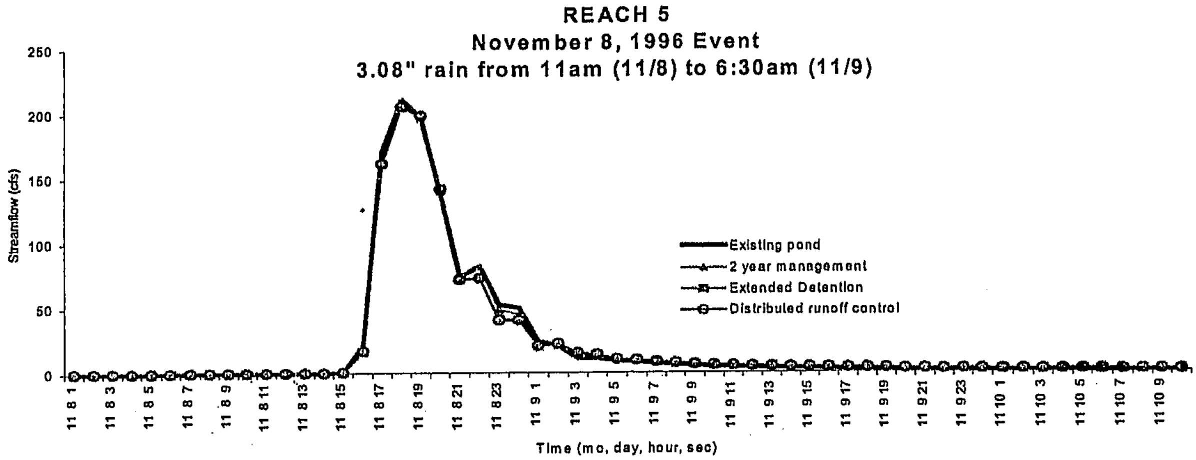

### REACH 1, Below Pond 1
**January 27-28, 1998 Event**
**1.98" rain from 7pm (1/28) to 5:30pm (1/29)**

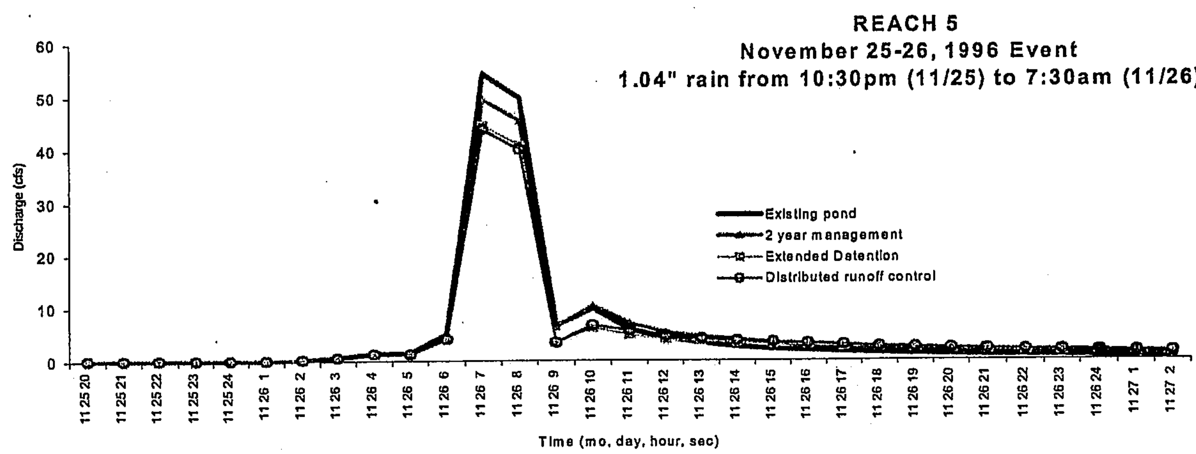


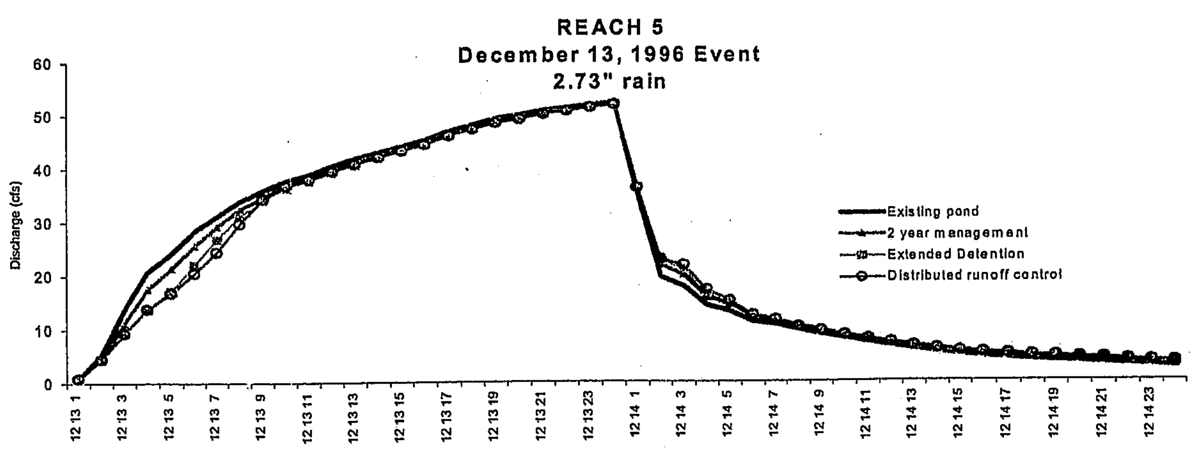

### REACH 1, Below Pond 1
**February 4-5, 1998 Event**
**1.62" rain from 3:30am (2/4) to 6:00pm (2/5)**



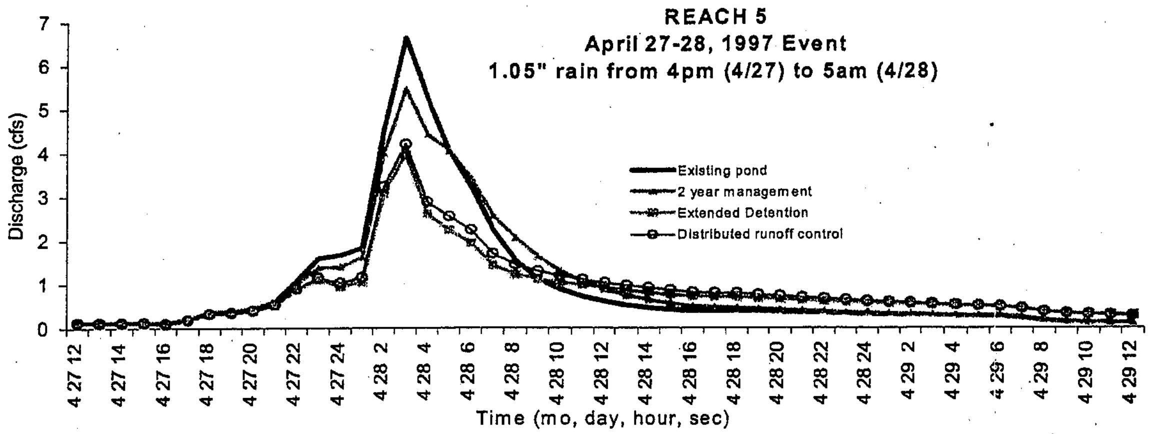
## Stormwater Management Scenarios

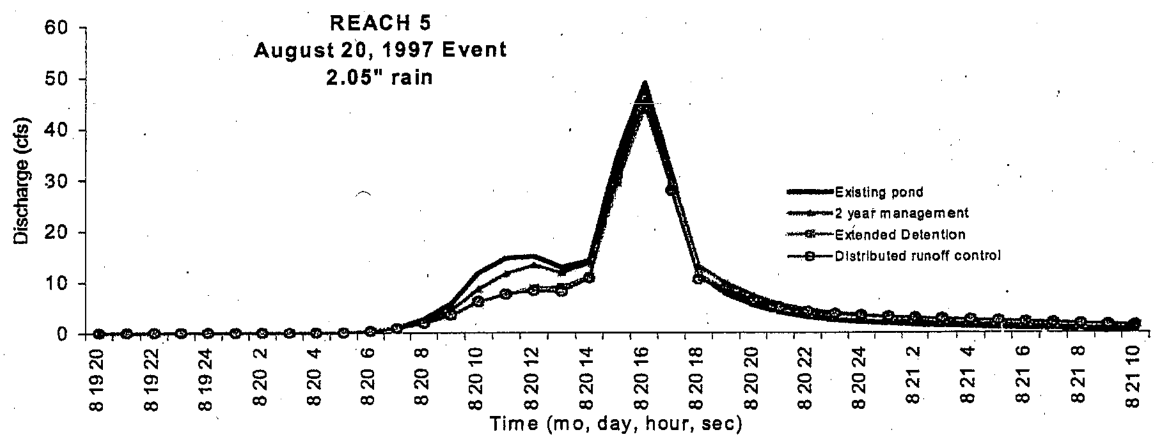


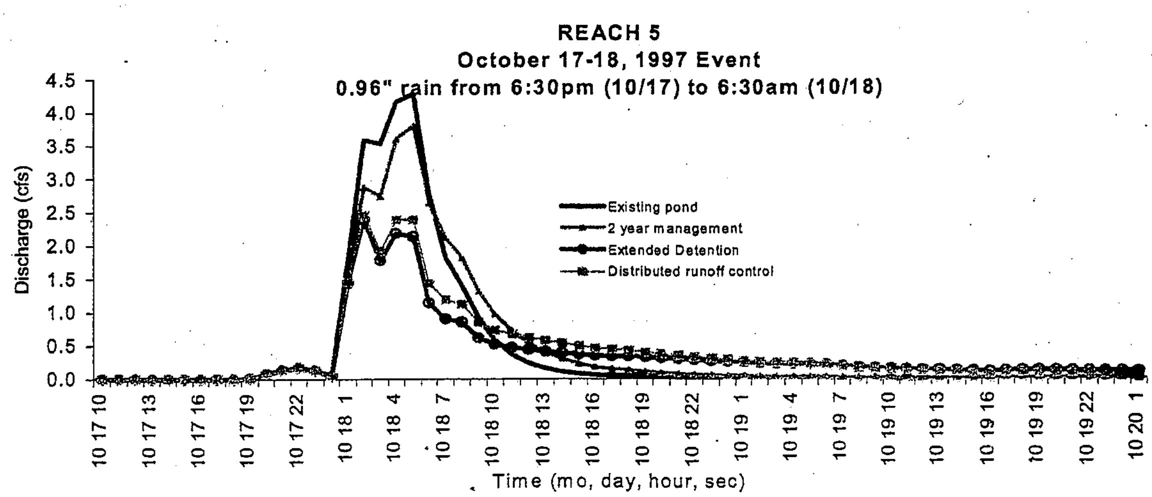



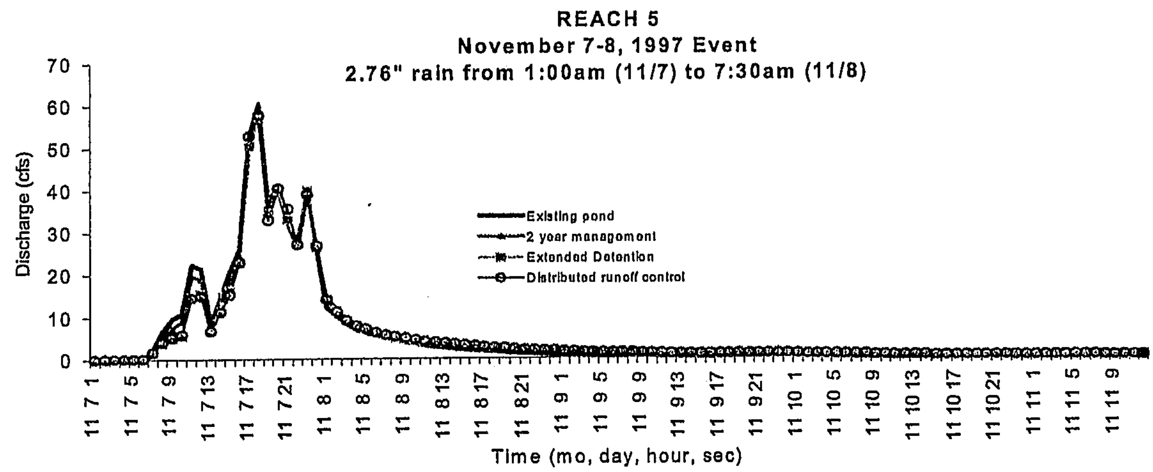
**Stormwater Management Scenarios**
cont'd

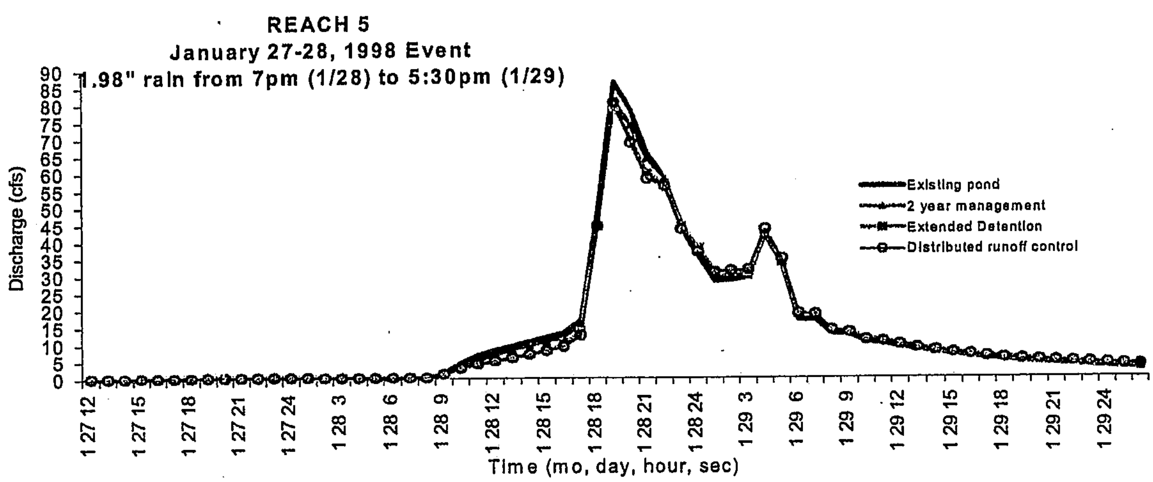


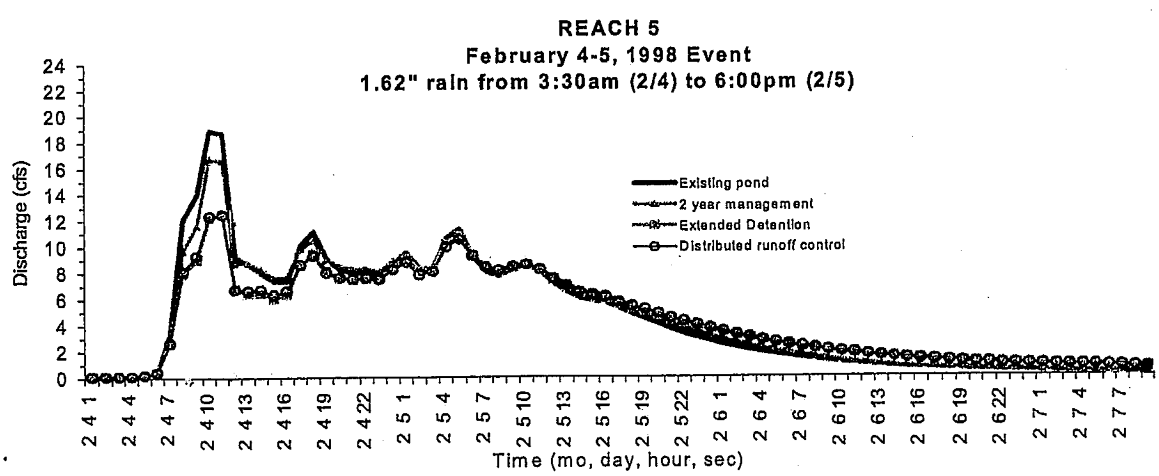



## Stormwater Management Scenarios
cont'd



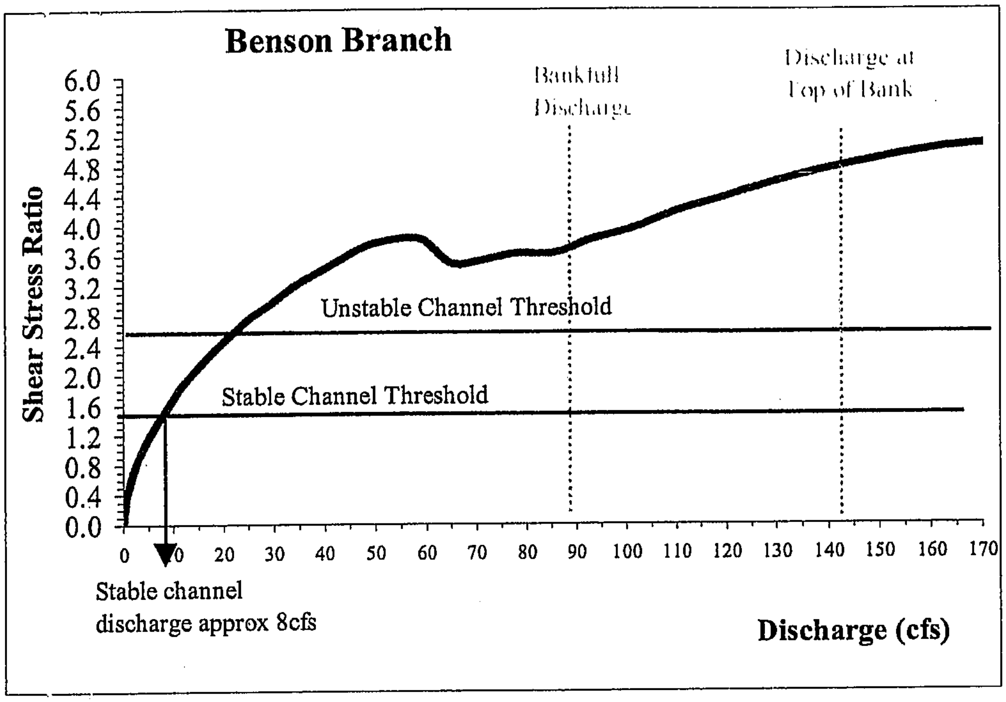



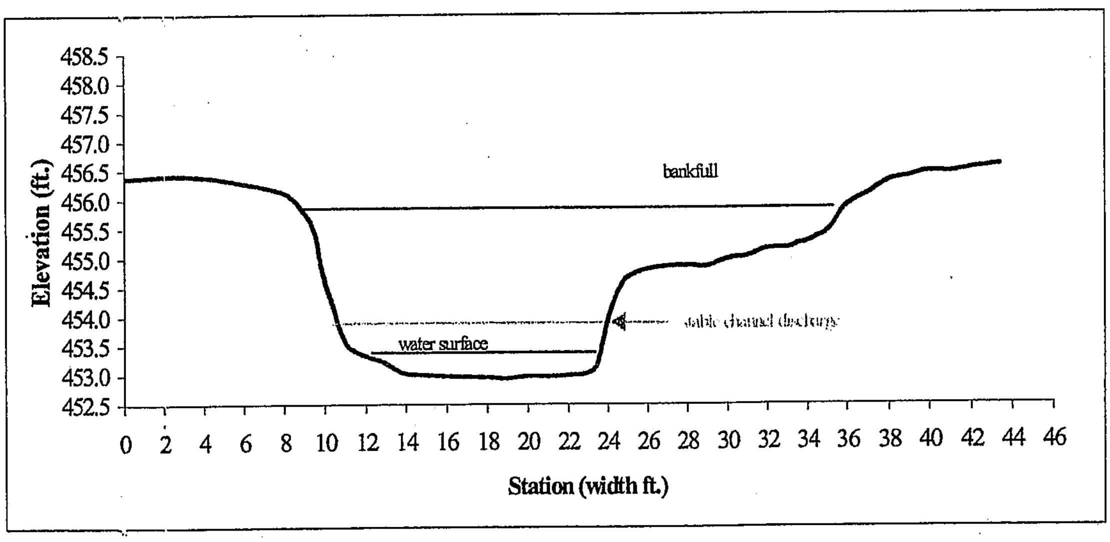
Appendix E

Channel Stability Analysis at Benson Branch, Reach 5

## Channel Stability Analysis




## Channel Cross-section at Reach 5, on Benson Branch



# *Stream Channel Enlargement Due to Urbanization*

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*Abstract.* Stream channel enlargement occurs in response to the change in streamflow regimen accompanying urbanization. This empirical study relates the imputed increase in channel cross-sectional area to detailed land use data and other information for 78 small watersheds near Philadelphia. Important differences between the effects of various types of impervious land use are observed: large channel enlargement effects are found for sewered streets and area of major impervious parcels such as parking lots, and much smaller effects are observed for unsewered streets and impervious area involving detached houses. Relatively low channel enlargement effects are attributed to all types of impervious development less than 4 years old and also to street and house area more than 30 years old. The influence of impervious development on channel size is found to be significantly related to topographic characteristics of the watershed, to the location of impervious development within the watershed, and to man-made drainage alterations. Although the relative importance of these interactive factors proves difficult to establish, the most critical determinant of the amount of channel enlargement resulting from a given level of urbanization appears to be basin slope.

It has been widely recognized that urban development in a watershed causes change in streamflow regimen [*Anderson*, 1968; *Leopold*, 1968]. The process of urbanization tends to increase the peak flow magnitudes through the spread of impervious area, which increases the volume of runoff, and through drainage alterations (such as storm sewerage), which facilitate the movement of runoff through the basin. The study reported here has focused on a phenomenon that accompanies the increase in peak flows, namely, the enlargement of stream channels due to urbanization.

Observers in the past have suggested that stream channels tend to maintain a state of quasiequilibrium with the flow regimen of the stream such that there is a constant frequency of overbank flow. This frequency has been estimated at approximately 1.5 years [*Leopold*, 1964]. For watersheds affected by urbanization, *Leopold* [1968] has hypothesized that stream channels tend to enlarge by an amount sufficient to maintain a similar quasiequilibrium state under the altered flow regimen; thus the amount of channel enlargement would be roughly proportional to the increase in the 1.5-year flood. Although recent findings have caused the common bank-full frequency hypothesis to be seriously questioned [*Kilpatrick and Barnes*, 1964], the notion that stream channels respond to urbanization by enlarging in roughly the same proportion as the increase in peak flows does appear intuitively plausible.

Channel enlargement resulting from urbanization has been considered an important subject of investigation for two reasons. First, the process of channel enlargement itself involves a serious reduction in the aesthetic and recreational value of the stream and incurs monetary costs in many instances. For small streams this effect must be considered one of the major negative impacts of urbanization on stream quality. Second, a more detailed treatment of urbanization is possible when studying channel enlargement than when studying peak flow increase, since in the former case it is not necessary to rely on stream gage data and hence a larger sample of streams can be employed. This circumstance has allowed the present study to consider empirically a wide variety of factors relevant to the hydrologic impact of urbanization.

## CHANNEL MEASUREMENT PROGRAM

The study has involved 78 watersheds 1–6 $mi^2$ in area in the Pennsylvania portion of the

Philadelphia metropolitan region (consisting of Philadelphia, Bucks, Montgomery, Delaware, and Chester counties). All watersheds were located in the Piedmont physiographic area. Fifty of the sample watersheds contained some degree of urbanization in the form of large-scale residential, commercial, or industrial development; 28 watersheds contained only rural land uses.

The channel measurement process consisted of stretching a tape across the stream so that it was level and perpendicular to the channel and measuring the vertical distance between the tape and the earth surface at 2-foot intervals. The depth of the channel at each point was computed by subtracting from each measurement the vertical distance between the tape and the point chosen as the bank top. These data were then used to compute the overall channel width, depth, and cross-sectional area for each cross section. (The computation of width and depth was based on the use of a computer program to find the best fitting rectangu- 'proximation to the channel cross section.)

...was found early in the study that the channels of many small streams are quite irregular and show considerable variation in cross-sectional area; this irregularity is particularly true for streams that drained urbanizing areas. For such streams it was obvious that only at a limited number of channel points could the channel be in quasiequilibrium with the flow regimen of the stream. Because of this finding no attempt was made to obtain measurements that would provide a complete characterization of the channel within a chosen reach. Rather, measurements were made only at points of apparent quasiequilibrium with streamflow.

Elaborate criteria for identifying quasiequilibrium channel points were developed as part of the study. These criteria are described in detail elsewhere [*Hammer*, 1971*a*]. The most important feature of these points is that the lower bank, the elevation of which defines the bank 'top' when computing channel dimensions, consists of a berm or bank segment that has been recently constructed by the stream, i.e., by deposition of sediment. The most commonly recognized situation in which such bank segments are found is that described in the familiar m ...er model of channel behavior, which speci... ...hat a meandering stream will erode its bank at the outside of a bend and will build a succession of new bank segments at the inside and thus a 'floodplain' will be constructed within the bend. An equally common situation found in the present study, however, was the existence of recently built bank segments at points where the channel had apparently become overwidened through scouring.

Four or more cross-sectional measurements were executed for most of the streams. The two variables of interest computed from these data were the channel cross-sectional area and the ratio of channel width to depth. The latter variable was formulated to test the possibility that channel enlargement due to urbanization typically involves a greater proportionate increase in channel width than in channel depth or vice versa. In preliminary studies the width to depth ratio was found to be correlated with channel slope and watershed area but showed no significant relationship to the degree of urbanization or to the apparent increase in cross-sectional area caused by urbanization. Thus the remainder of the analysis was concerned only with channel cross-sectional area, expressed as an average for each stream.

### LAND USE AND OTHER WATERSHED DATA

The collection of watershed data involved the use of a grid system for each watershed, the grid squares being 40 acres in size. Thirty variables pertaining to land uses and topographic characteristics were measured and recorded for each grid square. Each topographic variable (e.g., land slope) was measured as an average for land in the square. The grid square size of 40 acres was recognized to be inappropriately large for the consideration of factors such as land slope, since a great deal of variation can occur within such an area. A smaller size would have resulted in an infeasible number of grid squares to be considered however.

The set of land use measurements consisted of an exhaustive partitioning of the land area in each grid square into 17 categories. These measurements were executed by using aerial photographs (1 inch = 400 feet) and an intensive field survey of the sample watersheds.

The major focus of attention was land in impervious uses. Three basic categories of impervious area were considered: streets and sidewalks, houses and related impervious area, and all other impervious area. The first of these categories included the area of all paved streets, highways, rural roads, and expressways plus the area of paved sidewalks. The second included all impervious area associated with single-family (or two-family) houses, namely, the houses themselves; paved driveways, walks, and patios; and outbuildings, such as garages, sheds, and small barns. (These two categories will henceforth simply be referred to as 'area of streets' and 'area of houses.') The category of 'other' impervious area included a wide variety of land uses: commercial buildings, apartment houses, factories, airport runways, shopping centers, row houses, and especially parking lots. Approximately two thirds of the land in this category consisted of paved area instead of structures.

Within the 78 sa... ...tersheds these three categories of imperv...ous surface accounted for approximately equal portions of the total impervious area. Measurement of these variables was greatly facilitated by the fact that most of the impervious development in the sample watersheds was suburban and fairly recently constructed. Thus there was great uniformity in street widths and in house types, and also most of the other impervious area occurred in large parcels, e.g., shopping centers.

The length of time that impervious development had been in existence was expected to be important to channel enlargement. Therefore the impervious area in each of the three groups was subdivided into three age categories: area less than 4 years old, area 4–15 years old, and area greater than 15 years old. (This division was made possible by the fact that the aerial photographs were 4 years out of date and the topographic maps were approximately 15 years out of date at the time of the study.) Later in the study a fourth age category was created, applying only to street and house area; this category was the development constructed prior to 1940, as was estimated by using aerial photographs and the U.S. Census of Housing.

Another aspect of impervious development considered important was the existence of street storm sewerage. Although an exact determination of which street segments were underlain by storm sewers was not feasible, it was observed that the existence of curbing (usually associated with sidewalks) usually implied the existence of storm sewers and vice versa. Thus the procedure adopted was to consider any street segment with continuous curbing to be sewered. By using this definition, estimates were prepared for each grid square of the area of sewered streets and the area of houses fronting on sewered streets in each of the various age categories.

The major nonimpervious l... uses considered were nonimpervious d...ped land, wooded land, land in cultivation, a... 'open land.' ... nonimpervious developed ... category c...sisted primarily of lawn a... it was obtained for each grid square by ... tracting the a... rendered impervious from ... overall area o... land in intensive nonagricul...ral use. Open l... d was obtained as an overa... residual by sub...r... ting from total land are... the amount of ...oded land, land in cultivation, and land in in...sive nonagricultural use. Land in this category consisted largely of pasture and unused grassland.

The topographic and drainage system factors measured for each grid square were the average land slope, the length and average slope of the flow path from the grid square to the point at which the flow reached the stream channel, the length and slope profile of the stream channel from the point just mentioned to the watershed mouth, and the extent ... -made alterations to these drainage p...th ... ponents. With regard to drainage ...lt... s, any portion of the drainage path ... grid square to the watershed mouth ... considered altered if that portion co... a smooth artificial channel (e.g., a pi... cross-sectional area of which was at lea... ...arge as the probable area of the natural ... ...l that it replaced. A number of variable... ...dition to those given above were conside... ...luding several minor land uses; some of ... ...re mentioned below.

### FORM OF THE R... ...ION ANALYSIS

The dependent va... in the regression analysis was a quantity ... ing channel cross-sectional area; this qua... was termed the 'channel enlargement ratio. ...his variable incorporated an empirical re... ...nship between channel cross-sectional area an... watershed size for unurbanized basins. The relationship, estimated by using the 28 rural watersheds in the sample, was the following (with a correlation coefficient equal to 0.87):

$$\log C = 1.3945 + 0.6573 \log A \qquad (1)$$
$$C = 24.8A^{0.657}$$

where $C$ is the channel cross-sectional area in square feet and $A$ is the watershed area in square miles.

The channel enlargement ratio $R$ was computed as follows for each of the 78 sample watersheds:

$$R = C/24.8A^{0.657} \qquad (2)$$

The channel enlargement ratio consisted of the channel cross-sectional area of each stream as a proportion of the expected channel area in the absence of urbanization; thus the ratio expressed the amount by which channel size was imputed to have increased because of urbanization. (Whereas the subject streams were observed only once instead of over a period of time, the use of the term channel enlargement ratio is justified only by the fact that the ratio was indeed found to be strongly related to urbanization. This finding indicates that the channels of the urbanized streams had in fact enlarged relative to their preurbanization size.) Values of the enlargement ratio in the sample ranged from 0.7 to 3.8, the majority lying between 1.0 and 2.0.

The basic set of independent variables used to explain the channel enlargement ratio consisted of the proportions of the watershed area devoted to various land uses. In addition, a large number of interaction variables were formulated to investigate the possible influence of topographic and other factors on the effects produced by impervious land uses. An interaction variable was prepared by multiplying, for each individual grid square, a land use measurement times some other characteristic of the square, e.g., average land slope; the resulting figure was summed over all the grid squares and was divided by the watershed area.

Many of the grid square characteristics incorporated in the interaction variables were factors that would not be relevant to the amount of runoff yielded by the grid square itself but that might affect the contribution of the runoff to peak flows at the watershed mouth. An example of such a factor is the distance of flow from the grid square to the stream channel. In dealing with factors of this nature the following assumption was made: the relative importance of the various impervious land uses to channel enlargement when they are weighted by such a factor should be the same as their relative importance in unweighted form. This assumption led to the use of a single interaction variable for each factor, in which the factor was multiplied by a linear combination of impervious land uses for each grid square instead of by an individual land use. The coefficients in this linear combination were intended to equal the respective regression coefficients of the impervious land uses in unweighted form. This equality of coefficients was achieved by iterating the regression.

Two independent variables not involving land uses were included in the final regressions. One of these was a watershed shape index measuring the deviance of the watershed from circularity. This variable was the moment of the watershed about its center of mass (as a two-dimensional figure) divided by the moment of a circle having the same area. The other variable was a soil drainage index based on the USDA Soil Survey classification of soils as being 'well-drained,' 'moderately well-drained,' 'somewhat poorly drained,' or 'poorly drained.' Arbitrary scores of 4, 3, 2, and 1 were assigned to these soil descriptions, respectively, and the average score for soils in each watershed was computed. These two variables were both consistently strong in explaining the channel enlargement ratio.

## REGRESSION RESULTS

Four different sets of regression results were obtained as the final outcome of the data analysis. These regressions differed with regard to the grouping of impervious land uses, the treatment of age categories of impervious area, and the formulation of interaction variables. Only one set of regression results is reported here in full; this regression involved the least complex group of independent variables. The other regression results are described somewhat less formally in the following interpretive sections.

The regression reported here contains only one interaction variable, which deals with the average slope of the flow path from a given grid square to the watershed mouth. This average slope, expressed as a percent, was multiplied by the following linear combination of impervious land uses for each grid square: $0.83\,X_1 + 3.25X_2 + 3.79X_3$, where $X_1$, $X_2$, and $X_3$ denote the area of houses, the area of streets, and the other impervious area, respectively. The results of this regression are presented in Table 1.

The two variables not involving land uses were entered in the form of deviations around their means. Thus note that the constant term in the regression represents an estimate of the effect on channel enlargement of land not included in any of the independent variables dealing with land uses. (A watershed containing none of these land uses and having average values of the soil drainage index and the watershed shape index would have a channel enlargement ratio equal to the constant term 0.90.) The land category not included among the independent variables was open land, which accounted for approximately 30% of the land area in the sample watersheds.

TABLE 1. Multiple Regression Results with Channel Enlargement Ratio as Dependent Variable

| Independent Variable | Regression Coefficient | Standard Error of Coefficient |
|---|---|---|
| Land in cultivation | 0.3896 | 0.1291 |
| Wooded land | −0.1518 | 0.1151 |
| Land in golf courses | 1.6416 | 0.5538 |
| Area of houses >4 years old fronting on sewered streets | 0.8291 | 0.7462 |
| Area of sewered streets >4 years old | 3.2499 | 0.8998 |
| Other impervious area >4 years old | 3.7855 | 0.4486 |
| Nonimpervious developed land plus impervious area <4 years old and unsewered streets and houses | 0.1870 | 0.0890 |
| Interaction variable: average slope of flow path to watershed mouth | 0.2966 | 0.0350 |
| Watershed shape index | −0.1990 | 0.0776 |
| Soil drainage index | −0.1072 | 0.0247 |
| Constant term | 0.9025 | |

Multiple $R^2 = 0.9813$.

Each of the regression coefficients for independent variables dealing with land uses represents the difference between the channel enlargement effect of the given use and the effect of open land. Thus the effect of land in cultivation, for example, would be $0.90 + 0.39 = 1.29$. For the major impervious land uses the channel enlargement effects include interaction with slope of flow. To calculate typical values of these quantities, the following relationship was estimated for watersheds in our sample: $S = 1.87A^{-0.4}$, where $A$ is watershed area and $S$ is the average slope of flow to the watershed mouth from all points in the watershed as a percent. Thus the typical channel enlargement effect associated with the sewered street area, for example, could be calculated as the constant term plus $3.25(1 + 0.297S)$, or $0.90 + 3.25[1 + 0.297(1.87A^{-0.4})]$. The estimated channel enlargement effects of the various land uses for a typical 1-mi² watershed are presented in Table 2.

The values listed in Table 2 would be multiplied by the proportions of watershed area devoted to various uses to yield an estimate of the channel enlargement ratio in any particular situation. For example, an urbanized 1-mi² basin might have 70% of its area in nonimpervious 'developed' land and 10% in sewered streets, 10% in houses fronting on sewered streets, and 10% in other impervious area; the expected channel enlargement ratio in this case would be $0.7(1.08) + 0.1(2.19) + 0.1(5.95) + 0.1(6.79) = 2.25$. The predicted channel cross-sectional area in square feet would be $2.25 \cdot 24.8 = 55.8$.

*General evaluation of results.* In considering the overall levels of effect predicted by these results, it is useful to compare them with the findings of earlier studies investigating the effect of urbanization on peak flows. *Leopold* [1968] has summarized the results of a number of these studies. He focused on the ratio of average annual flood after urbanization to average annual flood before urbanization for a 1-mi² watershed. This ratio is related in tabular and graphic form to two urbanization variables, the percent of watershed area rendered impervious and the percent of sewered watershed area.

The values described by Leopold for the average annual flood ratio are quite similar to the values indicated by this study for the channel enlargement ratio. For example, the estimated average annual flood ratio of a 100% impervious, 100% sewered watershed would be just under 7. This value corresponds closely to the channel enlargement effect found in the present study for other impervious area, which would have to be the predominant land use in a totally impervious watershed. As another example the hypothetical watershed mentioned earlier, 10% of its area being in each of the three major impervious uses, would have an average annual flood ratio of approximately 2.5 (corresponding to 30% impervious area and 60% sewered area). This value is similar to the estimate of 2.25 obtained here for the channel enlargement ratio. (A more complete comparison of the results of this study and the data summarized by Leopold is presented in *Hammer* [1971*b*]. A number of assumptions regarding typical characteristics of urbanization were required to convert the variables used in this study to the form considered by Leopold; these assumptions are too involved to describe here.) The general agreement between the results for channel enlargement and the data pertaining to average annual flood is consistent with the common [illegible]nk-full frequency hypothesis and tends to [illegible]d support to the procedures employed in this study.

Although the equation reported above should yield accurate predictions of channel enlargement in most situations, it is likely that the effects attributed specifically to sewered street area and other impervious area are biased upward. Intercorrelation between the various aspects of urbanization has allowed these variables to 'borrow' causal influences that properly should have been attributed to other factors. The factors whose influences have been borrowed would include the following in order of probable importance: alterations to the natural drainage system, impervious area of unsewered streets and houses, and impervious area less than 4 years old. It was possible to establish the separate influences of some of these factors in other forms of the regression involving complex variables (see equation 3 below). But the possibility of bias due to intercorrelation was present throughout the analysis.

*Land uses other than impervious area.* The results obtained for nonimpervious land uses were generally reasonable. Land in cultivation was found to have a positive influence relative [to] open land, and land in forest was found to

TABLE 2. Channel Enlargement Effects of Land Uses in a 1-Square-Mile Basin—Version 1

| | |
|---|---|
| Land in cultivation | 1.29 |
| Wooded land | 0.75 |
| Land in golf courses | 2.54 |
| Area of houses >4 years old fronting on sewered streets | 2.19 |
| Area of sewered streets >4 years old | 5.95 |
| Other impervious area >4 years old | 6.79 |
| Nonimpervious developed land plus impervious area <4 years old and unsewered streets and houses | 1.08 |
| Open land (residual category) | 0.90 |

have a negative influence. This pattern was observed in all regression results, including regressions that involved only the 28 rural streams. The coefficient for land in forest was not significantly different from 0 at the 5% level in the regression reported above; but this variable was retained because of its statistical significance in other regressions and because of the stability of its estimated effect throughout the analysis. (A similar situation prevailed for area of houses fronting on sewered streets.)

Quite a large regression coefficient was obtained for land in golf courses. This land use was expected to have a greater impact on channel size than most nonimpervious land uses, owing to its drainage characteristics and to the watering of fairways during summer months.

Nonimpervious developed land was an important land use in the sample watersheds, accounting for more than 20% of the total land area surveyed. A small but significant positive coefficient was obtained for this land use both when it was combined with impervious area categories (unsewered streets and houses and impervious area less than 4 years old) and when it was entered singly. The positive coefficient was not unexpected, since the developed land category contained a variety of land uses besides residential lawn area. This category included some land in intense use (such as unpaved parking areas) and much land immediately bordering sewered impervious surfaces (such as highway medians and land between streets and sidewalks). The estimated effect for this use must be viewed only as an overall average for developed land not actually rendered impervious; the possibility remains that the effect of established lawn area per se might be less than that of open land.

*Types of impervious area.* The largest effect on channel enlargement was estimated for other impervious area. Area of sewered streets was next and was followed by area of houses fronting on sewered streets. This pattern was maintained in all regressions, although the relative sizes of estimated effects did vary considerably (see Table 2 versus Table 3).

It was hypothesized that the great influence attributed to other impervious area and the relatively small importance attributed to houses had to do with the size of impervious parcels involved. Parking lots and large buildings might yield storm runoff in such quantities that the proportion lost to infiltration or depression storage during flow to the stream would be minimal, whereas this proportion might be large for runoff from houses, driveways, patios, and so on. A partial test of this hypothesis was conducted by giving separate consideration to other impervious area found in parcels greater than 5 acres in size (which accounted for approximately half the total); but the regression coefficient for this subcategory did not differ significantly from the coefficient for the remaining other impervious area.

The large effect estimated for other impervious area is striking in view of the fact that this effect holds without regard to drainage facilities present. (Drainage facilities specifically serving these areas were not surveyed in the study.) To test for the possible importance of proximity to sewered streets, a variable was formed in which other impervious area was weighted by the density of sewered streets for each grid square. No importance was attributed to this variable in the regression however.

Low effects were obtained throughout the analysis for area of unsewered streets and houses fronting on unsewered streets. As was indicated earlier, it is believed that the importance of street sewerage to the effects produced by street and house area was somewhat exaggerated. One suspected reason for this exaggeration is the existence of a negative correlation among urbanized watersheds between the proportion of streets that are unsewered and the efficiency of the drainage facilities for streets that are sewered. This correlation would lead to a downward bias in the regression coefficient for unsewered streets and an upward bias, relative to average conditions, in the coefficient for sewered streets (and similarly for houses). A second reason is the probable existence of correlations between the proportion of unsewered streets and various characteristics of the surrounding nonimpervious land. (See the discussion of age of impervious area below.)

In one version of the regression the area of streets in residential districts with detached houses was added to the area of houses to form a single 'residential impervious area' category. Two variables relating to this category were entered in the regression, i.e., sewered residential impervious area and all residential impervious area weighted by average land slope, as a percent, for each grid square. The coefficients obtained for these variables were, respectively, 2.02 and 0.18 (see equation 3). Although the importance attributed to land slope may be questionable, the channel enlargement effects thus yielded for sewered versus unsewered area are probably more reasonable than those obtained in other formulations. For residential impervious area located in a 1-$mi^2$ basin on land with a slope of 5%, the estimated channel enlargement effects would be approximately 4.2 for sewered area and 2.0 for unsewered area; if land slope were 10%, the effects would be 5.2 and 3.0.

A special category of houses, not heretofore mentioned, was given separate treatment in the study. This category included houses having direct, underground connections between gutter downspouts and the storm sewerage system. This sort of construction was found only in the city of Philadelphia, where these connections are required by building codes. The estimated channel enlargement effect of houses possessing this feature was consistently very high and similar to the effect of other impervious area. Thus in the final runs of the regression this land use was included with other impervious area.

*Age of impervious area.* The length of time that impervious development had been in existence was important in the study in two different ways. First, since stream channel enlargement must require some length of time to be accomplished, one would expect that the observable effect of a parcel of impervious area on the stream channel at a given time would be positively related to the age of the parcel at that time. Second, the results of the study have suggested that relatively old impervious area, in existence more than 30 years, may have less effect on the stream channel than development constructed somewhat more recently.

With regard to the first of these considerations, an assumption was made that the relative importance of age of development should be the same for all types of impervious area. For example, if the influence of street area 4–15 years old is only 75% as great as the influence of street area more than 15 years old, owing to the time element in channel enlargement, then the same percentage should apply to house area and to other impervious area in these two age categories. The incorporation of this assumption in the analysis reduced the number of parameters to be estimated but made it necessary to iterate the regression, i.e., to estimate the influences associated with type of impervious area and age of impervious area in successive rounds.

In the initial phase of analysis (before separate consideration was given to impervious development more than 30 years old) the following results were obtained for the various age categories. Impervious area less than 4 years old was found to have no positive influence relative to open land, but impervious area 4–15 years old was attributed an influence fully as large as that of development more than 15 years old. In response to these results, area 4–15 years old and area more than 15 years old were simply added together for each impervious area type, and impervious area less than 4 years old was deleted from the regression as a separate factor. This action yielded results such as those shown earlier.

It was observed in the analysis that watersheds with relatively old development tended to have relatively low values of the channel enlargement ratio. Thus separate consideration was given to area of sewered streets and area of houses fronting on sewered streets that had been in existence for more than 30 years at the time of the study, i.e., were built before 1940. The result was that notably lower effects were estimated for area more than 30 years old than for area 15–30 years old, especially in the case of house area. (The level of statistical significance that can be attached to the addition of a separate >30-year category is indicated by the fact that in regressions for which this step simply involved adding one independent variable the variable would be found significant at the 5% level but not at the 1% level.)

A likely explanation for this finding is that the drainage facilities serving older residential areas might tend to be relatively poor, either because they were underdesigned to begin with or because they have deteriorated over time. It is probable that an equally important cause, however, was the association between age of development and characteristics of the land not rendered impervious. Older residential developments tend to have more trees, shrubbery, and other dense vegetation than newer developments; also the soil structure itself has had more time to recover from being disturbed (if indeed it was ever disturbed). The negative influence of these factors on runoff and stream channel enlargement would, in the absence of other relevant variables, be attributed to the age of impervious area.

Regardless of which explanation is more important, it is difficult to say whether the relatively low effects estimated for older impervious area should be interpreted to mean that the impact of any residential development should be expected to decrease eventually or whether the low effects pertain only to development of a certain type that was built primarily before 1940.

When streets and houses more than 30 years old were given separate consideration in the regression, the estimated influence of impervious area 4–15 years old and area 15–30 years old differed appreciably. Also positive regression coefficients were obtained for impervious area less than 4 years old, although these were never statistically significant. The channel enlargement effects estimated in this case are shown in Table 3.

*Influences of natural watershed features.* One of the principal aims of the study was to state the importance of watershed features and the location of development within a watershed in such a fashion that the channel enlargement effects of development in different watersheds or at different points in a given watershed might be compared. The desire to obtain results that would be usable for intrawatershed comparisons made it necessary to consider topographic factors pertaining to individual grid squares instead of overall basin indices. Also the inter-

TABLE 3. Channel Enlargement Effects of Impervious Land Uses in a 1-Square-Mile Basin—Version 2

| | |
|---|---|
| Impervious area <4 years old and unsewered street and house area | 1.08 |
| Area of houses fronting on sewered streets | |
| Houses 4–15 years old | 3.36 |
| Houses 15–30 years old* | 4.15 |
| Houses >30 years old† | 1.08 |
| Area of sewered streets | |
| Streets 4–15 years old | 4.20 |
| Streets 15–30 years old* | 5.16 |
| Streets >30 years old† | 3.76 |
| Other impervious area | |
| Area 4–15 years old | 6.26 |
| Area >15 years old | 7.99 |

* Built after 1940.
† Built before 1940.

action variables incorporating these factors had to be rather complex in form to avoid certain anomalous situations. (See the discussion at the end of this section.) This enterprise was successful in that statistically significant results were obtained for a set of variables having the desired properties. However, serious questions of interpretation remain.

The major factors to be considered were the watershed size, the distance and slope of flow to the stream channel (i.e., from a given grid square), the distance and slope of flow in the stream channel to the watershed mouth, and the existence of portions of the drainage network that had been altered by man. An additional factor, average land slope in the grid square itself, was used to weight individual types of impervious area (instead of weighting the linear combination of all impervious uses).

As a basis for the formulation of variables it was hypothesized that the impact of impervious development on channel enlargement at the watershed mouth is reduced, relative to potential impact, by an amount that is positively related to the intervening distance of flow (in unaltered portions of the flow path) and negatively related to the slope of the flow path. Slope would be relevant because of its influence on flow velocity and also because it would serve as a surrogate for the amount of flood detention (e.g., overbank storage) that would be likely to take place during peak flow periods. With regard to drainage alterations it was hypothesized that flow in fully altered watercourses (as defined earlier) would not involve any reduction in impact. These assumptions are of course naive in view of the complexities of basin hydrology.

Flow to channel and flow in channel were treated in two separate variables, each of which involved distance divided by a function of slope (for individual grid squares). The quantity used to weight impervious development in the final form of the flow to channel variable consisted of the flow distance to the stream channel divided by the square of the average slope of this flow path. The flow in channel variable was based on measurements of the length, slope, and drainage area of a series of separate channel intervals. The quantity used to weight impervious development in this variable consisted of a summation, over all channel intervals relevant to a given grid square, of the interval length divided by a slope index pertaining to the interval (see equation 3 below).

The influence of watershed size was intended to be expressed by way of a third variable involving only watershed area $A$ raised to some exponent. Therefore steps were taken to remove the association with watershed size from the flow to channel and flow in channel variables. Both these variables were divided by the quantity $0.985A^{0.524}$, which represented an estimate (based on the current sample) of the average flow distance in miles from all points in a watershed to the watershed mouth. In addition, the slope index used in the flow in channel variable incorporated an adjustment for the association between channel slope and drainage area. Thus the influence of watershed size was effectively isolated in the watershed size variable. The form of this variable that worked best was $A^{-0.5}$ with a positive coefficient.

The equation estimated in this phase of the analysis (the variables not relating to impervious development being omitted) is presented in (3). In this equation the impervious development in each grid square is multiplied by a term that could vary from 1.3 (for development located at the mouth of a 1-mi² watershed) down to very small or even negative values. Within the sample watersheds studied, however, the variation in this term was generally moderate.

The influence attributed to watershed size per se is somewhat smaller than that expected.

According to the estimated equation the average effect of impervious development in a typical 5-mi² watershed (net of the effect of open land) would be approximately 13% less than the average net effect of the same type of development in a 1-mi² watershed.

$$R = 1.0 + \frac{1}{A} \sum_i (2.02 M_i + 0.180 N_i P_i + 4.71 Q_i) \left\{ 1.0 + 0.302 A^{-0.5} - \left[ \left( 1.98 \frac{S_i}{T_i^2} + 0.126 \sum_{k \in \Omega_i} \frac{U_k}{V_k} \right) \Big/ 0.985 A^{0.524} \right] \right\} \quad (3)$$

where

- $R$, estimated channel cross-sectional area for a given watershed, square feet;
- $A$, watershed area, square miles;
- $i$, subscript denoting individual grid square in the watershed;
- $M_i$, sewered residential impervious area more than 4 years old (consists of sewered street and house area in single-family residential districts), square miles;
- [illegible], total residential impervious area more than 4 years old, square miles;
- $P_i$, average land slope in grid square $i$, percent;
- $Q_i$, other impervious area more than 4 years old, square miles;
- $S_i$, length of unaltered portion of the flow path from grid square $i$ to the stream channel, miles;
- $T_i$, average slope of flow to channel, percent;
- $k$, subscript denoting individual channel interval in the watershed;
- $\Omega_i$, set of channel intervals across which runoff from grid square $i$ drains during flow in channel;
- $U_k$, length of unaltered portion of channel interval $k$, miles;
- $V_k$, slope index for channel interval $k$.

(The channel slope index for interval $k$ equals the average slope for the interval, as a percent, divided by the quantity $1.00 W_k^{-0.53}$, where $W_k$ is the average drainage area of the stream in square miles in interval $k$. This quantity represents expected channel slope for the given drainage area, as estimated by using a large sample of channel intervals from the 78 sample watersheds.)

The influence attributed to both flow to channel and flow in channel was heavily dependent on slope. For a watershed with a typical channel …guration and typical slope values the re-…ion in net effect of impervious development due to flow to channel would range from 0% to approximately 20%; the range would depend on where the development was located and whether the flow path had been altered. In the sample watersheds with the lowest slope values, however, the imputed reduction ranged up to 50%. Very similar percentages were estimated for reduction due to flow in channel (although the typical influence per unit distance in this case was only one third as great as that for flow to channel).

Thus for an 'average' location in a typical watershed the reduction in net effect of impervious development associated with both flow components would be on the order of 20%, relative to the net effect if the development were located at the watershed mouth or if the entire flow path had been altered by man. Conversely, the typical result of altering (e.g., piping) all watercourses in a basin would be to increase the net effect of impervious development by 25%. If the channel enlargement ratio had been 2.2 before alteration, the new value would be 2.5.

The importance attributed to drainage alteration in the above equation is considerably smaller than that expected on the basis of other studies involving peak discharge [*Anderson*, 1968]. Furthermore, other regression equations containing no mention of drainage alteration were able to explain channel enlargement equally well (see below). Throughout the analysis, variables expressing the extent of drainage alteration as a separate factor were tested but were found to lack statistical significance. This result can be partially explained by the high correlation between drainage alteration and the amount of impervious development, which would allow the effects of the former to be attributed to the latter. (A particularly high correlation exists with area of sewered streets, since street sewerage almost always implies alteration of a significant portion of flow to channel.) However, the result does indicate that drainage alteration is less important than land use characteristics for basins such as those studied here.

As described earlier, a form of the regression was also employed in which only one interaction variable, involving the overall slope of flow, was used. Surprisingly, the level of statistical explanation in this form of the regression was fully as great as that in the form just discussed. The ability of the overall slope of flow variable to substitute for variables expressing watershed size, flow to channel, flow in channel, and land slope was due to the high levels of intercorrelation between these variables. The fact that the substitution was possible reflects negatively on the probable accuracy of the coefficients shown in (3).

Use of the equation involving the overall slope of flow variable to compare the influence of impervious development at different locations in a watershed could lead to erroneous conclusions. For example, because of the typical upward concavity of watercourses, the average slope of flow to the watershed mouth is likely to increase with distance of flow; but the influence of impervious development presumably decreases with distance of flow. Thus the overall slope of flow factor must be considered in the nature of an overall basin index, which is suitable only for comparing the average effects of development in different watersheds.

## SUMMARY AND CONCLUSIONS

The study has indicated that important differences exist between the channel enlargement effects of different impervious land uses. The effect of impervious area associated with detached houses is small unless the gutter downspouts connect directly with storm sewers. The effect of street and sidewalk area is large if the streets are sewered but is small otherwise. Other impervious area, which consists primarily of contiguous impervious surfaces exceeding 1 acre in size, has a very large channel enlargement effect. Influence on channel size increases with the length of time that impervious development has been in existence, as is expected, but relatively low effects are observed for street and house area more than 30 years old. The latter fact may or may not indicate that the impact of residential development tends to decrease eventually.

The impact of impervious development appears to be positively related to channel slope, slope of flow to channel, and slope of the developed land itself (in the case of residential area). It is negatively related to the distance of flow to channel and flow in channel, excepting portions of the flow path that have been altered by man. The channel enlargement ratio associated with a given intensity of development also bears a mild negative relationship to watershed size. Although the relative importance of the various topographic and drainage system characteristics is difficult to establish, the slope factors appear to be more influential than distance factors (which involve location of development within the watershed). Man-made alterations to the drainage system other than sewerage of the impervious area itself are attributed a milder influence than that expected.

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# URBANIZATION AND THE NATURAL DRAINAGE SYSTEM— IMPACTS, SOLUTIONS, AND PROGNOSES

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# Urbanization and the Natural Drainage System—Impacts, Solutions, and Prognoses

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## Introduction

Drainage systems consist of all of the elements of the landscape through which or over which water travels. These elements include the soil and the vegetation that grows on it, the geologic materials underlying that soil, the stream channels that carry water on the surface, and the zones where water is held in the soil and moves beneath the surface. Also included are any constructed elements, including pipes and culverts, cleared and compacted land surfaces, and pavement and other impervious surfaces that are not able to absorb water at all.

A landscape can be divided into individual drainage basins, each of which contains all the elements of a drainage system that contribute water to one particular stream channel. Conversely, each channel collects the rainfall from its own individual drainage basin, and that channel's form is a consequence of the runoff processes that are active in its basin.

The collection, movement, and storage of water through drainage basins characterize the hydrology of a region. Related systems, particularly the ever-changing shape of stream channels and the viability of plants and animals that live in those channels, can be very sensitive to the hydrologic processes occurring over these basins. Typically, these systems have evolved over hundreds or thousands of years under the prevailing hydrologic conditions; in turn, their stability often depends on the continued stability of those hydrologic conditions.

Alteration of a natural drainage basin, either by the impact of forestry, agriculture, or urbanization, can impose dramatic changes in the movement and storage of water. Some of these changes are intended, and they render the land more useful for the purpose for

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Plate 1. Ravine incision below suburban development in central King County, Washington. At this site, downcutting had proceeded at a rate of several feet per year since at least the mid-1960s, ultimately resulting in a multi-million dollar project to stabilize the surrounding area.

which it has been altered. Yet some of the changes are unintended and can have significant consequences. Flooding, channel erosion, landsliding, and destruction of aquatic habitat are some of the unanticipated changes that can also result from these alterations.

The alterations of a drainage basin accompanying urbanization

Robert Brittain

Plate 2. Overwhelmed drainage system in an area of rapid development. Flows that were once readily contained in culverts or roadside channels now expand well beyond the capacity of those facilities.

are among the most severe and potentially damaging. Their impacts have been inventoried by numerous studies (e.g., Wilson 1967; Seaburn 1969; Hammer 1972; Leopold 1973) because of the loss of both lives and property that sometimes result. With urbanization, stream channels expand catastrophically to consume adjacent land never before affected by either flooding or erosion; sediment inundates low-lying areas, seemingly far away from active channels; stormwater facilities are overwhelmed by frequent flows far beyond their design capabilities; and populations of aquatic organisms are decimated.

These changes have occurred far more rapidly than our understanding of *why* such impacts occur. Only since the 1980s have advances in the science of hydrology been applied to the conditions and needs of the urban environment. The result is a rapidly growing body of information on why certain impacts are occurring and on the measures that are necessary to effect genuine improvement.

What is lacking, however, is the development of parallel data on how well these measures actually succeed in reducing impacts: whether the undesired effects of urbanization on the hydrologic environment actually can be rolled back or avoided altogether. To date, measures have been taken that only partly address these impacts; even their limited performance has had insufficient time for a full evaluation. For example, most of the populous jurisdictions in the Northwest require some form of stormwater detention for urban developments, yet they require that only a *part* of the storm runoff be fully detained. The need for and nature of yet *more* stringent standards are only now being recognized in the technical community. Before the hydrologic performance of new methods can be demonstrated, however, their political and economic feasibility must be proven, as well.

This paper describes the causes and effects of urban-induced changes to the hydrology of a drainage basin. To understand the cause of change, the hydrologic behavior of the undisturbed basin first will be explained. The effects of development are then recognizable as the near-inevitable consequences of hydrologic changes. Therefore, effective solutions must not focus simply on the observed results (e.g., armoring an eroded stream bank), but rather on the underlying causes (e.g., replacing the amount of water storage capacity in the soil layer that was lost by paving over the ground surface).

## Hydrologic Background

### An Introduction to Storm Runoff

To understand the ultimate causes of urban impacts to the drainage system, the elements of the hydrologic systems must be described. First among these elements is *storm runoff*, that part of the rainfall that reaches a stream channel quickly—within a day or so of first falling on the ground. Typically, storm runoff is produced by any one of two methods. The first occurs if the precipitation falls on the soil surface more rapidly than the soil can absorb it, causing the excess precipitation to run over the surface of the land. This process was first described by Horton (1945) and is now called "Horton Overland Flow" (HOF). It is most common in regions of intense rainfall and shallow, vegetation-poor soils, notably the arid and semi-arid northwest interior east of the Cascade Range. Water moves quickly from the hillslopes into the channel, and all parts of the drainage basin contribute to the storm runoff in the channel.

Conversely, where rainfall intensities are generally lower than the rate at which the soil can absorb it, all of the precipitation can infiltrate where it first lands. Water still moves downslope, but it also flows below the surface. This mechanism, known as the *subsurface flow regime*, has been most thoroughly described by Dunne (e.g., Dunne, Moore, and Taylor 1975). It predominates where rainfall is gentle and vegetation is lush; the coastal regions of the Pacific

Northwest provide one of the best examples on the North American continent. Water moves very slowly off the hillslopes, and only those parts of the basin near the stream itself will contribute to the storm runoff.

As a storm continues, flow patterns and runoff quantities can change. Where overland flow dominates, the major change is a rapid reduction in soil infiltration capacity as the ground first gets wet. The change typically occurs within the first hour, with the infiltration capacity then remaining constant (e.g., Strahler 1975). Under the subsurface flow regime, this change is unimportant, as the soil still has adequate infiltration ability to absorb water as rapidly as the rain can fall.

Under the subsurface flow regime (where runoff moves predominantly *through*, not over, the soil), a different process causes a change in runoff quantity. Water tables in the soil will rise as water is added to the subsurface. If those water tables lie at or near the surface, their progressive rise expands the area of saturated ground in the drainage basin. In these saturated areas, new precipitation cannot infiltrate because the soil has no space to absorb more rainfall. They are typically located towards the bottom of slopes, in seasonally wet valleys, and adjacent to streams and lakes. Therefore, the total area of saturated ground, and thus the area where overland flow will occur, expands as the water table rises. This expansion occurs over a period of days, and so the part of a drainage basin that is contributing rapid storm runoff to the channel steadily increases during the course of a single storm. Expansion also tends to intensify through an entire storm season (Hewlett and Hibbert 1967).

## What Controls the Magnitude of Storm Runoff

*Basin Size.* A variety of factors influence the discharge (rate of runoff) from a specific site or an entire drainage basin. These factors must be recognized to understand, and correct, alterations to basin hydrology. Most fundamental of the factors influencing discharge is the sheer size of the basin; the amount of runoff from a "large" basin depends primarily on the total *volume* of water that is released, usually over a period of many days. In contrast, "small" basins will be most strongly affected by the *rate* at which water is introduced to the basin and transported to the outlet stream. The boundary between these two size categories is very broad, but it lies in the range of a few hundred square miles. Most of the concern for urban development and stream hydrology focuses on "small" basins.

The storm runoff from a small basin will respond rapidly to changes in the rate of precipitation or runoff. Any factor that affects either the amount of water that enters the channel or the speed with which water moves through the basin will alter the magnitude of the discharge. Land-use conditions are particularly significant in determining these factors. Thus, differences or changes in the land use, generally muted in the hydrologic response of a large basin, dominate the hydrologic response of a small basin.

*Land-Use Factors.* The character of the land surface exerts a profound effect on runoff processes, which in small basins are almost immediately expressed by the rate of storm runoff. Typically, only a fraction of the total precipitation falling on a basin actually reaches the stream channel. The remainder either: (1) never reaches the ground and is evaporated off the surfaces of vegetation; (2) enters the ground but is transpired by plants or evaporated from the soil; or (3) percolates deeply to the regional groundwater system and is lost to the stream (as storm flow, at least). Of the fraction that reaches the channel, its time of arrival is controlled by whether it flows primarily through the subsurface or over the surface (subsurface flow vs. HOF), how quickly it is collected into open channels on the hillside, and whether it is detained in reservoirs (either within the soil column or in surface lakes or ponds).

Changes in land use will affect basins in the two hydrologic regimes differently. Where overland flow predominates, much of the precipitation reaches the channel under all storm conditions, regardless of the level of urban development. Runoff moves at rapid, surface-flow rates; although those rates depend in part on the nature of the conduit (e.g., flow in a smooth pipe is faster than in a meandering channel), the variability in speed is not high. Thus, urbanization in regions of HOF (in which water runs over the land surface) may increase the net percentage of precipitation that reaches the channel, even though the underlying runoff processes have not changed significantly.

Where subsurface flow predominates, however, much of the precipitation normally never reaches the channel; it is instead lost to evaporation and transpiration. The remaining water moves towards the channel through the subsurface, generally quite slowly and with ample opportunity for long-term storage in the soil. If the land surface is paved or otherwise modified to intercept more of that water, transport rates will increase many-fold and intervening storage is vastly reduced. Thus, in areas where the subsurface flow regime once predominated, urbanization will have a particularly dramatic effect on the magnitude of runoff because the fundamental processes of runoff generation are being altered. It is this situation, ideally exemplified in the broad lowlands of the Pacific Northwest, that provides the information for the following discussion.

# Identifying the Effects of Urbanization

## Introduction

Human activities accompanying development can have irreversible effects on drainage-basin hydrology, particularly where subsurface flow once predominated. Vegetation is cleared and the soil is stripped and compacted. Roads are installed, collecting surface and shallow subsurface water in continuous channels. Regrading eliminates previously undrained depressions. Subsurface utilities intercept yet deeper subsurface water and rapidly pipe it out of the basin as surface flow. Building construction is the most visible impact, but merely the final link in a long chain of hydrologic changes. Construction adds impervious areas that intercept rainfall before it can reach the soil surface.

These changes produce measurable effects in the hydrologic response of a drainage basin. Most dramatic, and most often studied, is the increase in the maximum discharge associated with floods. Synopses of such studies (e.g., Hollis 1975; Saver et al. 1983) all report similar results. Depending on the percentage of urbanized area, peak flows can increase five-fold over natural conditions, with the greatest changes observed for the most frequent flood events.

Other related hydrologic changes also occur from urbanization, but they require more sophisticated methods for predicting resultant stormwater runoff. Therefore, it is necessary to understand the past and present methodologies of hydrologic modeling which are the numerical tools by which runoff can be studied. Modeling methodologies will allow us to understand the changes wrought by urbanization, and show why many of the efforts to control runoff problems have not been entirely successful.

## Hydrologic Modeling to Predict Runoff

*Event-Based Models.* Well over one hundred years ago, the fundamental predicting equation of runoff was developed (Mulvany 1851). The *Rational Runoff formula* related the runoff rate to the simple product of the rate of rainfall, the basin area, and the runoff coefficient—a number that expressed the fraction of the rain falling on a basin that actually contributed to the flood peak. The runoff coefficient is adjusted for different land uses and land covers. Thus, highly pervious, forested ground is typically assigned a value of near zero (i.e., almost no water reaches the channel); pavement is given values approaching 100 percent.

An improvement of the Rational Runoff formula is the Soil Conservation Service's *Curve-Number Method* (U.S. Soil Conservation Service 1975), which was developed to improve hydrologic prediction. Greater flexibility is allowed in the matching of basin conditions with runoff coefficients; the results have been more extensively calibrated with actual data.

Both models, however, suffer from fundamental shortcomings. First, the storm of interest is a single event, typically of a few hours or a day in duration. Second, these methods assume that all parts of the basin function hydrologically in the same way. Finally, the models poorly represent the paths that runoff actually follows in and through a drainage basin. Thus their applicability to a particular drainage basin, particularly one where subsurface flow is a dominant runoff process, is rather poor (e.g., Hawkins 1975; Burges et al. 1989).

*Continuous Hydrologic Models.* Recent computer modeling efforts seek to correct the shortcomings of these earlier attempts. One such model, in relatively widespread use in the Pacific Northwest, is the Hydrologic Simulation Program Fortran or "HSPF" (U.S. Environmental Protection Agency 1984), based on the Stanford Watershed Model IV (Crawford and Linsley 1966). HSPF is a continuous hydrologic model that uses hourly (or more frequent) precipitation data as input over the entire period of simulation, which may be many years in length. The model keeps a running account of the amount of water within various hydrologic storage zones, both surface and subsurface, and divides the rainfall into these zones as it falls. Individual storm "events" are not discriminated; the actual rainfall record, over time, determines how the hydrologic system responds.

To date, the most comprehensive modeling effort with this model in the Pacific Northwest used 21 gage sites in five basins in Washington State's King and Snohomish Counties (Dinicola 1989). This work, and its continuance and expansion in selected basins elsewhere in King County (King County 1989, 1990*a*, *b*), provide the basis for much of the hydrologic analysis and discussion that follows.

## Runoff Changes from Urbanization

Continuous hydrologic models can display a long-term record of streamflow out of a basin. Therefore, they can reveal a variety of changes resulting from urbanization. Such changes are easily simulated on the computer by applying the same rainfall input to the same land area, but under different simulated land uses. In contrast, older work has emphasized only the increase in peak discharges that accompany urbanization. This emphasis primarily has reflected

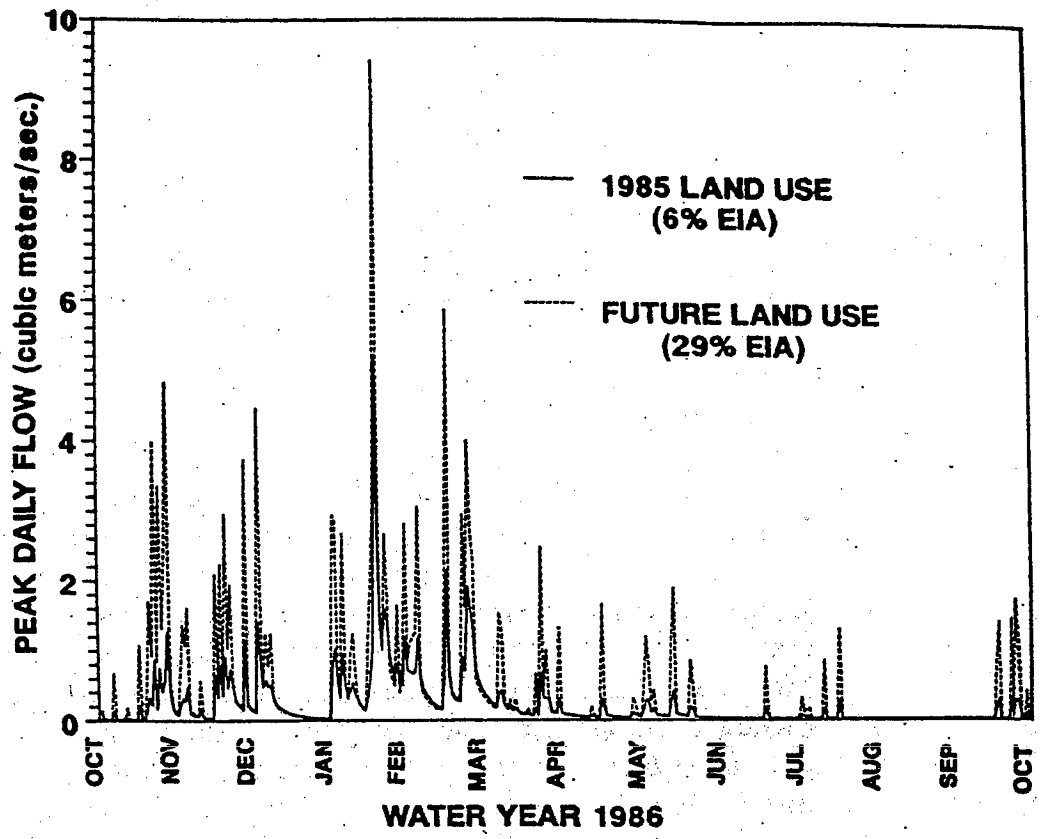


Fig. 1. One year of simulated streamflow for a 13-km² drainage basin under differing land uses, simulated with the Hydrologic Simulation Program Fortran (HSPF). Parameters characterize existing (1985) land cover (6 percent effective impervious area [EIA]) and projected future land cover (29 percent EIA).

the ease with which these particular data can be collected, not necessarily their overriding significance.

A sample simulation with a continuous hydrologic model is shown in Figure 1, displaying the differences in runoff between relatively low and high levels of urban development. In the highly urbanized case, the major flow peaks are amplified, and many new peaks also appear. These result from smaller storms, some of which produced no storm runoff at all before development, but which now can generate substantial flows.

Thus, urban development does more than simply *magnify* peak discharges; it also creates entirely *new* peak runoff events. As a result, floods of any given discharge will occur much more frequently after urbanization. For example, if the discharge of the 2-year flood doubles following urbanization, then clearly the (smaller) discharge must now be exceeded more frequently than every two years, on average. These changes in frequency can be quite dramatic; dis-

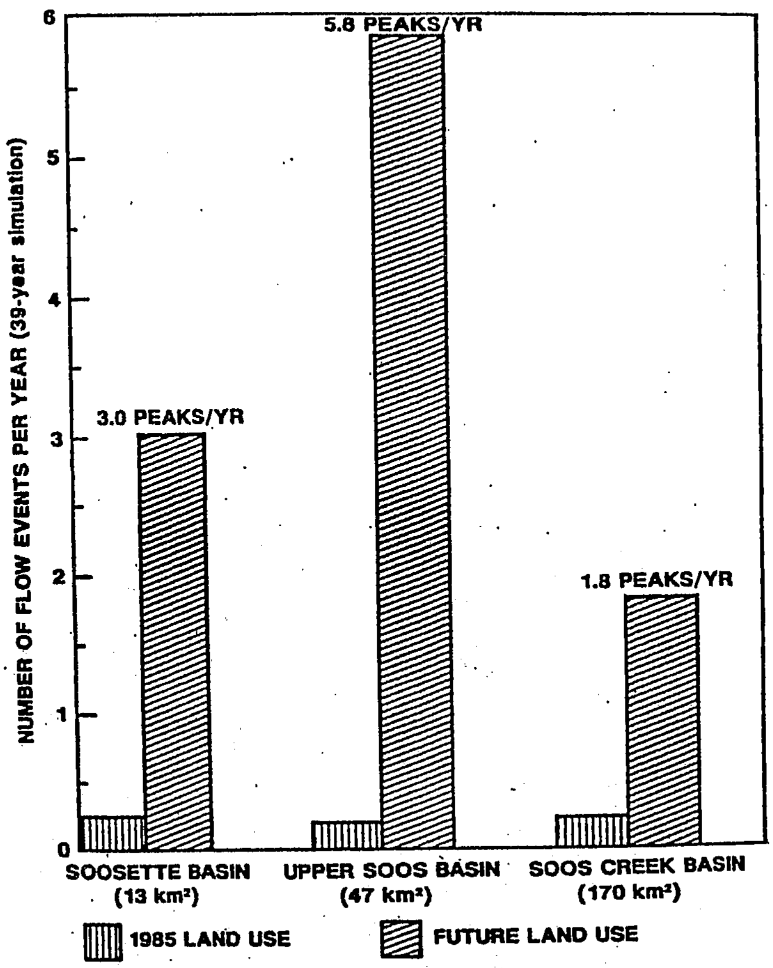


Fig. 2. Simulation of change in the frequency of "large" flood peaks at three points in the Soos Creek basin, as a result of future urbanization. The discharge of the present five-year flood peak is used as the threshold for defining "large" peaks; its future recurrence shows a nine- to 29-fold increase.

charges once associated with large, multi-year or multi-decade storm events now inundate the urban basin one or more times per year (Fig. 2).

## Alteration of the Channel Corridor from Urbanization

Urban development not only increases flows, it also encroaches on the stream corridor—the zone surrounding the channel that influences the hydrology and biology of the flow. Frequently, this leads to the clearing of streamside vegetation, particularly trees. The consequences of this clearing are two-fold: first, less wood enters the channel, depriving the stream of stabilizing elements that help dissipate flow energy and usually help protect the bed and banks

Derek Booth

Plate 3. Complete obliteration of streamside corridor accompanying urban development. Reestablishment of channel diversity is no longer possible, because the necessary woody debris cannot be introduced from the adjacent land area.

from erosion. Second, the overhead canopy of a stream is lost, eliminating the shade that controls temperature and supplies leaf litter that enters the aquatic food chain.

These impacts are not unique to urban development; logging has generated a legacy of such impacts, with a number of studies assessing their effects (see, for example, Salo and Cundy 1987). But although logging imposes a dramatic change on a stream system, with proper management the ultimate result is only temporary (Fig. 3). With urban development, however, the changes are permanent. Their net effects were measured during the period 1982–1985 over a number of lowland streams in suburban King and Snohomish counties, Washington (Metro 1988) and show a consistent pattern; "rural" streams show many fewer impacts to the channel corridor than do their "urban" counterparts.

## The Consequences of Runoff Changes and Corridor Alteration

### Expansion of the Stream Channel

*Background.* In urban basins, stream channels are faced simultaneously with an increase in flow magnitudes and a decrease in

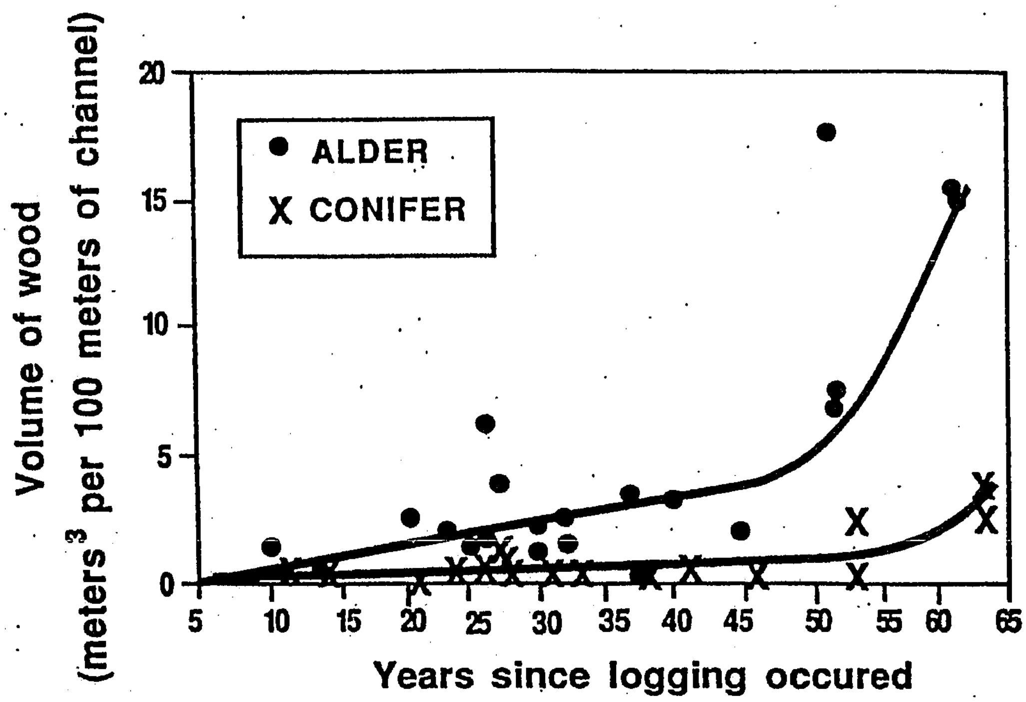


Fig. 3. Rate of recovery of woody debris in small stream channels following logging of second-growth forests in western Washington (from Grette 1985).

channel-stabilizing wood. Either factor alone would be sufficient to increase channel erosion, but in combination their consequences are magnified. Furthermore, the flow increases themselves can cause an increase in the wash-out of wood from the channel; even if the corridor remains intact, the rate of wood replacement back into the channel is ultimately limited by the rate of tree growth. Under the best of circumstances, accelerated wood removal will not be compensated by accelerated regrowth and replacement. More commonly, however, urbanization eliminates the corridor altogether, which means that wood is not replaced in the channel at all.

As a result of these factors, channel widths and depths increase throughout urban areas (e.g., Hammer 1972; Leopold 1973). But these increases do not always occur in the same fashion. Although channel dimensions can increase gradually in response to gradual increases in the flow regime, changes in channel dimensions are usually more sporadic and abrupt. Such events often happen during particular storms, where a single large flow can annul periods of stability that may have spanned many years (Fig. 4).

*Channel Incision.* More profound than channel expansion is channel incision, which is the nearly uncontrolled downcutting of a stream bed, usually in response to an increase in the flow rate (Booth 1990). Although expansion of a channel is damaging under any

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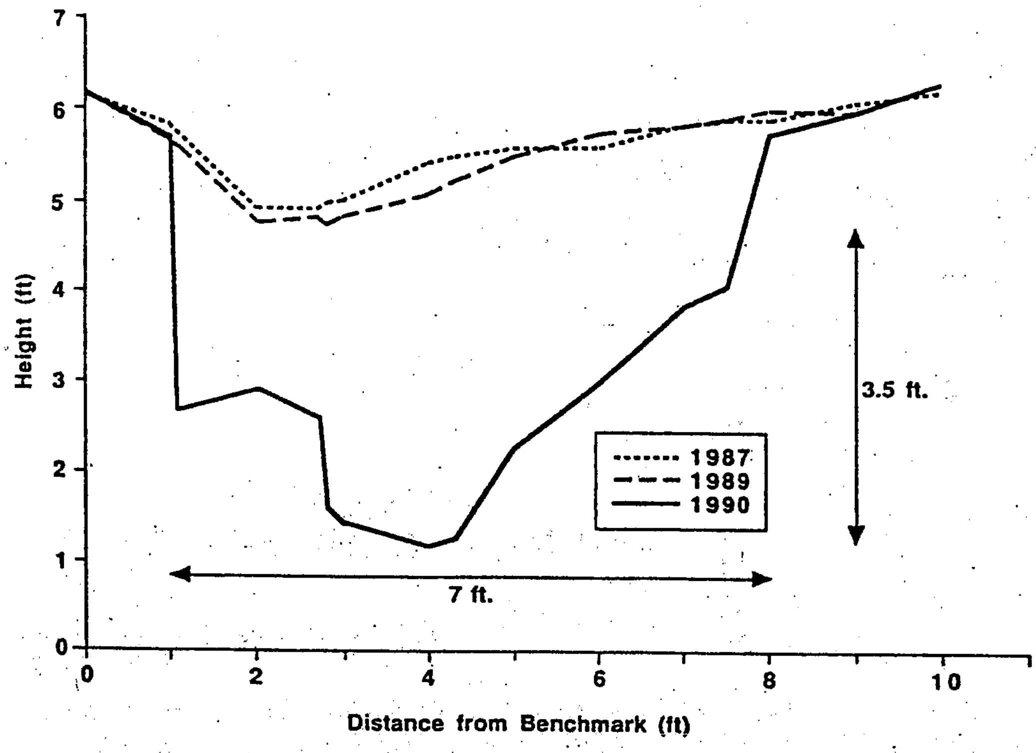


Fig. 4. Cross-sections measured in a three-year period in a small urban stream draining about one km². A large storm, with a recurrence of several decades, occurred in January of 1990 and resulted in significant downcutting at this site.

circumstance, true incision is particularly problematic because the resultant stream is generally devoid of habitat diversity and the eroded sediment can clog the downstream system. Based on studies of recently incised channels in King County, Washington, a number of conditions must be met for incision to occur in humid drainage basins in the Pacific Northwest. High flows in particular are necessary, but in addition we usually observe steep channel gradients; easily erodible substrate (typically sand); and few or only widely spaced controls on the *grade* (bed slope) of the channel—typically these are large logs lying on the channel bed that anchor the bed elevation.

Incision represents a loss of geomorphic balance between the forces of downcutting (the moving water) and the resistance of the stream bed to erosion (determined by sediment size, channel roughness, and the action of anchoring debris). Urban development influences two of these factors: the magnitude of flows and the persistence of wood in the channel. The other factors are intrinsic to the basin, so urbanization does not always cause incision. Where it does occur, however, the results can be truly spectacular and economically devastating (Booth 1989); the cost of rectifying the problems can be in the millions of dollars (e.g., King County 1987*a*, 1990*c*).

## Disturbance Frequency

*Disturbance and Watershed Dynamics.* Disruption of a stream channel by very high flows is a natural process that occurs erratically but with characteristic time scales. During such events, the channel form itself is affected—stream banks erode, large cobbles and boulders are moved on the bed, woody debris is repositioned or washed out, pools are filled, and bars are scoured. Although the form of the channel is disrupted and the quality of the aquatic habitat is degraded, the effects are temporary. Lower flows, still sufficient to remobilize sediment within the affected channel reach, begin to "rebuild" the stream. New wood from the stream corridor enters the flow and is positioned anew. The "disturbance" ultimately results in a reformed, rejuvenated environment that continues for many years in a state of relative stability (Lisle 1986; Booth and Barker 1988).

In the Pacific Northwest, this process of episodic disturbance has always occurred on channels that have, historically, supported large anadromous fisheries. Under natural conditions, rates of disturbance and subsequent recovery varied widely, even between streams of the same watershed. Habitat elements were altered but had periods of stability that lasted from a decade to a century, or more. Salmonids in these lowland streams have evolved with this historic disturbance regime.

That which constitutes a "very large" flow, sufficient to alter the stream channel and the habitat within it, is largely empirical. Work done throughout the streams of the Pacific Northwest and in other humid environments suggests that large-scale channel disruption can be caused by flows larger than about the 5-year flood (e.g., Carling 1988; Sidle 1988).

*The Effects of Urbanization.* Hydrologic changes imposed by urban development profoundly affect the disturbance frequency in developing basins. This phenomenon can be investigated with the HSPF hydrologic computer model, using a sample drainage basin in southwest King County and northwest Pierce County, Washington (the Hylebos Creek basin; Booth, Fuerstenberg, and Barker 1990). Modeling of such a basin allows direct comparison between the flood events during a 40-year simulation period, using either fully forested or fully developed land uses as variables.

Using the historic rainfall record, modeling the Hylebos Creek basin with a simulated forest cover produces eight floods at or above

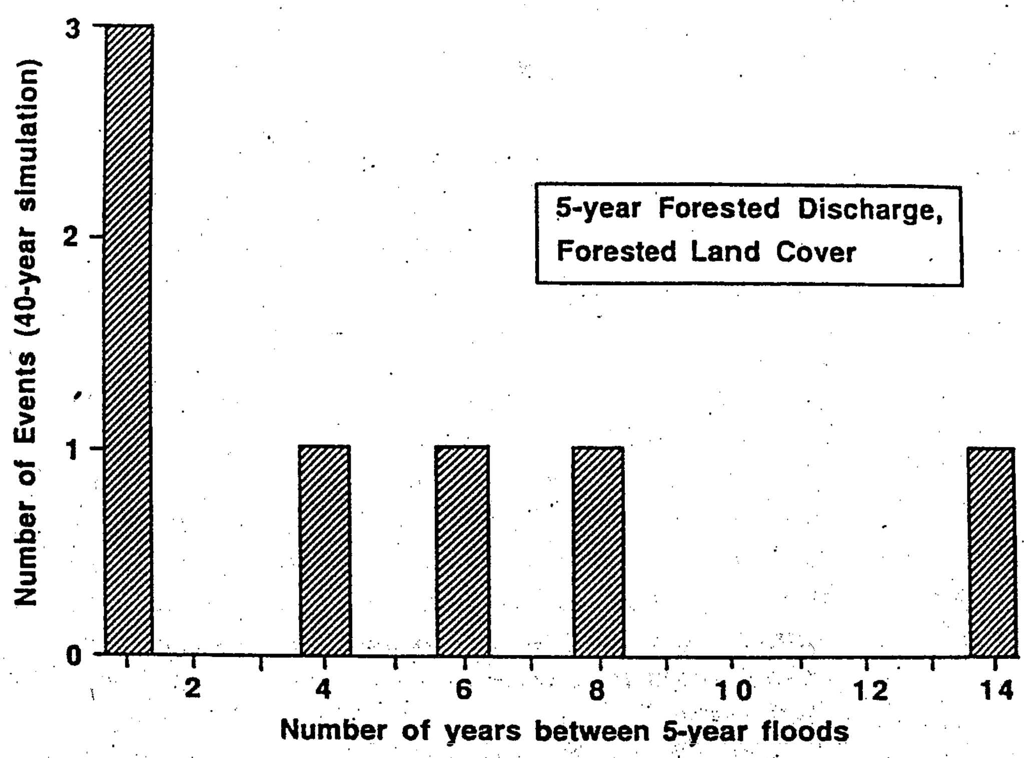


Fig. 5. HSPF simulation of the Hylebos Creek basin in southwest King County, Washington, under fully forested land cover. Bars show the number of years separating discharge events of 5-year recurrence or greater. The *average* separation is 5 years (40 years of simulation, 8 events), but the actual spacing varies from one year (i.e., successive years) to 14 years.

the 5-year discharge (Fig. 5). The intervals between such floods are quite variable, with as much as 14 years between two events, and others coming in successive (water) years.

In contrast, the same rainfall over the fully developed basin yields only one year *without* a flood of this discharge or greater (Fig. 6). Indeed, the average year has over five such flows, with a median interval between them of less than a month. If we consider only floods above the forested 10-year discharge, the results are virtually identical but even more severe—only three such events are seen in 40 years with fully forested land use, but in the developed basin they occur almost monthly.

### A Summary of the Physical Effects on Channels

As a result of channel changes due to increased flows and altered corridors, urban streams have a characteristic "look" to them. Their beds are uniform, with few pools or developed riffles to break up the planar surface. Channel banks are raw and near-vertical, with

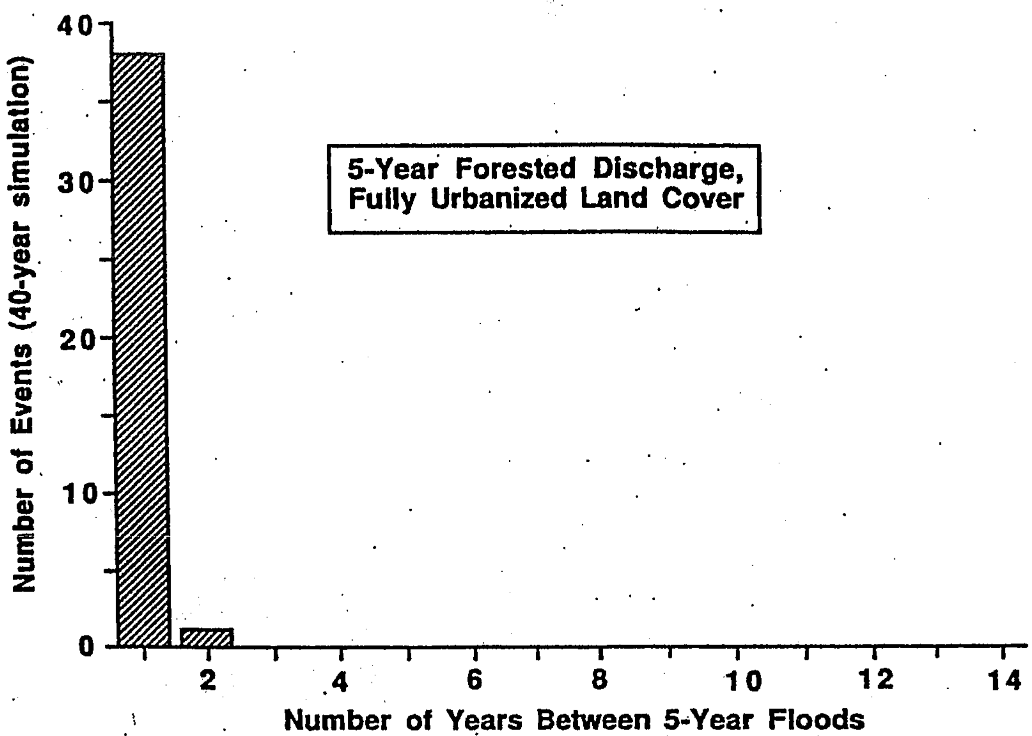


Fig. 6. Forty years of HSPF simulation of the Hylebos Creek basin under fully urbanized conditions (about 40 percent effective impervious area). Discharges at or greater than the 5-year forested event occur in every year except one (compare with Fig. 5).

incisions of one to many feet. The erosion of adjacent steep banks is constantly adding new sediment. Woody debris is small and sparse, and it is either suspended above the level of the flow or is only weakly anchored in the bed. Finally, the aquatic organisms that thickly populate equivalent drainages in undeveloped settings are nearly absent, reflecting the cumulative impact of physical and chemical changes to the stream and its substrate.

These characteristics occur throughout all the streams of an urban drainage basin. Almost no variability is observed, despite inevitable differences between drainage areas, and the channels have become homogeneous and sterile. These channels resemble the aftermath of a debris torrent, in which a flood of water and sediment moves catastrophically down a valley and leaves a nearly uniform, barren channel in its wake (e.g., Benda and Zhang 1989). But although such a channel can normally rebuild its long-term form, the urban channel has perhaps only days before another disturbance of nearly equivalent magnitude begins the process all over again. Thus hydraulic and biologic diversity is eliminated both within a stream and between streams. As urban development fills a watershed, its effects spread as well. These effects are so pervasive, affecting all

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Plate 4. Boardman Creek in the North Cascades following the passage of a debris flow. Although the channel is presently homogeneous and rather sterile, abundant woody debris adjacent to the channel and a likely future of only moderate flood levels will allow rapid rebuilding of a diverse, productive stream.

aspects of the runoff processes, that only the most well-directed efforts at control have any hope of reversing the trend.

## Correcting the Impacts of Urbanization

### Principles

In the face of pervasive changes to basin hydrology, it is almost impossible to eliminate the impacts of urban development. In the Pacific Northwest, the major path by which water moves, namely subsurface flow, is almost wholly replaced by another. Travel times from hillslope to stream channel shorten by a factor of one hundred or more. Soil pores below the ground surface, which have sufficient volume to store a substantial fraction of the annual rainfall itself, are isolated from precipitation by paving. Stream channels are bridged, piped, or simply obliterated. Finally, the dissolved and suspended constituents carried into the channel are dramatically changed as bare soil is exposed through construction and the chemicals accompanying modern urban life are introduced into the watershed.

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Plate 5. A typical level of urban development in the Puget Sound region, where precipitation is largely denied access to the subsurface and minor stream channels are obliterated.

The underlying strategy for minimizing or avoiding the impacts of development is to reduce the amount of runoff and minimize the disturbance of the landscape, so some or all attributes of the predevelopment discharge and landscape are retained or mimicked. These impacts typically fall into three basic categories: (1) excessive runoff quantity, (2) lost channel and corridor integrity, and (3) degraded water quality (chemistry). Runoff quality, although a significant component of the net impact of urbanization, is presently the subject of intense regional study (e.g., Washington State Department of Ecology 1990) and will not be discussed here.

## Mitigation Strategies

*Water Quantity.* For many decades, the classic method of runoff quantity control has been detention storage. With this method, stormwater runoff is temporarily impounded at the outlet of a development site, ostensibly to detain the (increased) peak runoff and let out the water to the channel at a controlled rate equivalent to the predevelopment state. But the volume of stormwater draining from impervious surfaces is greater than from undeveloped land surfaces; therefore, if pre- and post-development rates are the same, the *duration* of such controlled flows must increase. Only where detention storage is very long (weeks or more), or where some or all of the runoff can be re-infiltrated into the ground, can the duration, as well as the peak discharge, be controlled.

Detention as a mitigation strategy depends on accurate prediction of runoff, both before and after development. Traditionally, both predictions are made by hydrologic models. Modeling the predevelopment condition is done because it is more convenient than making on-site measurements; modeling postdevelopment conditions is needed to design the detention storage before the development occurs.

In general, existing detention ponds do not achieve the goal of protecting the downstream system (e.g., King County 1987*b*) for three reasons. First, such ponds have an explicit design limit; flows that exceed this limit will overtop or bypass the storage area and experience little to no detention. Thus the largest storms are least reduced. Second, the design criterion for most ponds specifies a match of peak discharge but not of flow durations. Thus a given flow will occur for longer; if that flow is erosive, it will do work on the downstream channel for many times longer than in the predevelopment case.

The final reason for the failure of ponds to protect the downstream system is a result of the hydrologic modeling that is used in the pond design. Historically, either the Rational or an SCS Curve-Number method are used. These typically over-predict runoff from undeveloped surfaces (Barker, Nelson, and Wigmosta 1991), and they consider only single storms of one day's duration or less. Thus, these models specify an excessive rate of release from the pond, and they underpredict the amount of storage that is needed to control sequential storms properly. If built, the actual pond is already part full when the one-day storm "event" begins.

These shortcomings in pond design can be analyzed quantitatively. An exhaustive review of detention standards and pond performance using the HSPF model (Barker and Nelson 1989; Barker, Nelson, and Wigmosta 1991) shows the magnitude of the problem. For example, the standards that applied to new development in King County from 1979 through 1989 (King County 1979) actually multiplied the 10-year peak discharges by a factor between 3 and 10, depending on land use. The current (1990) standard for new King County development (King County 1990*d*) significantly improves performance but still yields up to a doubling of 10-year flows under the most intense land uses. Despite these seemingly poor results, both detention standards were more restrictive, in their day, than those imposed by any other jurisdiction in the Pacific Northwest.

The cost of stormwater control is typically measured by the volume of storage pond required, because of the otherwise useable land that is occupied. For example the volumes of these mandated ponds, measured in inches of depth per unit area of development, is at most 0.5 inches for the 1979 standard and about 2 inches for the 1990 standard. For less intense land use (i.e., residential instead of commercial), pond volumes are about 50 percent smaller. Thus, a 50-acre development would need to provide at most 8 acre-feet of storage (i.e., a pond covering 8 acres with a maximum depth of 1 foot or, more likely, a 2-acre pond with about 4 feet of water-level fluctuation).

These present volumes are significantly smaller than what more stringent potential standards might require. For example, improving the methodology of the 1990 requirements, by modeling longer storm events and slower runoff rates, requires pond volumes 25 to 50 percent larger. The performance of these larger ponds is significantly better; 10-year peak discharges match, or actually are reduced slightly, from predevelopment levels. Controlling flows out to the 100-year flood further increases the storage needs by a factor of about one third. And finally, to achieve a matching of pre- and postdevelopment flow *durations*, as well as flow peaks, even greater volumes are required. At this final level of control, up to three inches of storage are needed for residential land uses and six inches for a fully impervious drainage area. This represents a tripling of what is currently required; e.g., a pond for the hypothetical 50-acre development would thus occupy six acres, inundating over 10 percent of the site.

These maximum detention volumes, necessary to achieve genuine flow control, are close to the active storage in the undisturbed soil column. This active storage is the difference between the *field capacity* of the soil (the amount of water held in the soil pores after it has been allowed to drain freely) and the *saturation* water content of the soil (the ratio of pore volume to total soil volume). During the winter, water storage in the soil will typically fluctuate between full saturation (i.e., completely soaked) and its field capacity (i.e., damp but fully drained). With undisturbed soil depths of a few feet beneath western Washington forests, saturation water contents of about 40–50 percent, and field capacities of 20–30 percent, the active water storage is typically about 20 percent of the soil thickness, or about 6 inches to a foot in depth. Therefore, it is not surprising that the runoff conditions prior to development can be recovered only by providing a like amount of surface storage once the subsurface reservoirs are paved over.

*Channel and Corridor Integrity.* Superficially, protection of the stream corridor appears to be a simple proposition. Boundaries are demarcated, clearing and construction within them are prohibited, and the stream proceeds with no "awareness" of the activities beyond its zone of influence. The width of that zone of influence has been debated at length (e.g., Murphy et al. 1986; Budd et al. 1987). In general, any measurable benefits of wood recruitment, aquatic food supply, and shading appear to decline much beyond 100 feet from the stream. As a result, 100-foot-wide buffers (or other near-equivalent distances) have been recently proposed or adopted by a number of jurisdictions in western Washington (e.g., King County, Snohomish County, Federal Way, and Tacoma, among others).

Several factors reduce the actual effectiveness of buffers. First, existing land use is typically unaffected, and so existing impacts remain. Second, stream crossings by roads and utilities may be reduced but are not eliminated. Third, human intrusion still occurs, albeit more diffusely. Fourth, a buffer regulated during land development may not persist unaltered over time, especially once individual property owners take on the "oversight" role from the original permitting authority. Finally, a number of the impacts to the stream system pass through the buffer unimpeded. Most direct are the flow increases experienced in the channel from upstream development. In addition, adjacent construction can release substantial amounts of fine sediment, which can move as channelized flow through almost any width of buffer zone with little attenuation, and thence into the stream channel.

Buffers provide only a partial solution to channel impacts. They reduce, but cannot eliminate, the impacts at their outer margins from reaching the stream system. Where that stream system is still judged valuable, even these reduced impacts of development may have a measurable effect. In such cases, only decreased development activity in the basin will be successful at maintaining the stream resources.

This final strategy of reduced development for stream protection is not widespread in the Pacific Northwest. It is achieved through reduced zoning of specified drainage areas. It has formed the basis of one permanent and two interim land-use actions since 1989, affecting in total over 20 square miles in northeastern and southeastern King County. This strategy is only effective, however, where existing development and land-use patterns are favorable for continued low density. Therefore, it has no remedial benefit on an already degraded system.

# Prognosis: The Future of Urban Streams

## State of Understanding

Recent improvements in the application of hydrology to humid, urbanized drainage basins offer hope that the impacts of development—long cataloged but little understood—can be addressed with adequate tools. Although hydrologic modeling will undoubtedly continue to evolve, the transition from unverified, physically implausible models to calibrated, physically reasonable ones has already occurred. Results will continue to be refined, but they are unlikely to change as radically in the future as they have in the past.

These improved hydrologic models explain much of the past failures to control urban runoff. The actual complexity of stormwater runoff is ill-represented by the single parameters, such as "peak discharge," that are generated by overly simplistic models. Past efforts to control flows through detention storage can be demonstrated to fail, even at their limited appointed task; in contrast, improved pond designs perform credibly in simulation and are of physically reasonable dimensions.

The role of less quantifiable factors, such as stream corridors and substrate materials, are also recognized; these factors are not "modeled" but they demonstrably affect the function and response of channel systems. Corridor vegetation, in-stream woody debris, and the intrinsic tendency of the channel bed to erode contribute directly to stream and habitat degradation in several areas of western Washington; the implications are clear for the rest of the region. Landscapes of particular concern for stream impacts can be identified, based on the local application of relatively universal criteria.

## Applying Hydrologic Knowledge to Urban Planning

Although the present state of hydrologic knowledge is good and continually improving, the application of that knowledge to urban planning lags well behind. In part, delay is inevitable—information must be developed and then verified before it can become the foundation for widespread practical application. In the case of new methodologies, such as continuous hydrologic modeling, engineers and planners must first become educated as to its value and use.

However, the lag in application also reflects the practical implications of this new information. Because the mitigation measures that typically were applied over the last few decades are recognizably inadequate, any improvements in our understanding will unavoidably demonstrate the need for more extensive, and more expensive, mitigation. Larger detention ponds, broader undisturbed stream corridors, and lower-zoned densities all consume land otherwise judged "developable." Justifying the increased expense of additional mitigation is often difficult, because the tangible costs purchase only an intangible, often far-removed benefit—avoiding potential incremental damage to an off-site downstream system, perhaps at some time in the far-off future. Alternative strategies include building bypass pipelines for storm flows or more numerous, smaller detention facilities. However, these strategies add additional complexities that are only partly technical in nature, such as the need to acquire property beyond the development site or for long-term maintenance of multiple private facilities.

Most jurisdictions are unable to make the level of assessment and judgement needed to justify the high costs of effective mitigation. What are the values of the stream system in its predeveloped state? How effective will the mitigation be at protecting those values? Do the net benefits of mitigation justify their cost? Some of these questions do not involve quantifiable factors at all, and yet a consistent set of criteria, quantified as much as possible, would probably produce the most effective use of the mitigation effort that does occur.

Probably, a necessary first step is to develop studies on the scale of whole drainage basins, of the scope being prepared by King County (1990*c*, *e*; 1991) and only a few other jurisdictions nationwide. Through them, the resource values and problem conditions throughout a basin or a region can be assessed. Then efforts towards mitigation can be guided to greatest effectiveness, with the understanding that all parts of a drainage basin or a collection of drainage basins are not created equal. Measures that are appropriate to one part may be ineffective (or worse) in another (Moorehead et al. 1991).

Ultimately, however, such decisions are not made in the scientific arena but in the public one; there, calibrated hydrologic models are but one component of a debate in which due process, property rights, equal treatment, and economic hardship all share center stage. The last several years in western Washington suggest an overall trend towards greater mitigation of impacts and resource protection in the face of development, but the progress is by no means uniform or unidirectional.

Over the next decade, urban growth will force many more areas to address these questions, hopefully with better tools at their disposal. For other areas the development process will be largely complete. From those already developed areas, the consequences of past attention, or inattention, to the function of the natural drainage system provide an example for the rest of the region, where opportunities for mitigation or avoidance may still exist.

## Acknowledgments

Information in this discussion reflects the combined efforts of engineers, scientists, and land-use specialists in King County's Basin Planning Program, a multi-disciplinary effort to analyze, predict, and improve the surface-water problems and resources in the rapidly developing drainage basins of the County. Bruce Barker and Robert Fuerstenberg, in particular, have contributed greatly to the discussion here; the ongoing assistance and insights of Don Althauser, Roz Glasser, Ray Heller, Gino Lucchetti, Meg Moorehead, Ruth Schaefer, Arny Stonkus, Jeanne Stypula, Richard Thomas, and Mark Wigmosta also are gratefully acknowledged.

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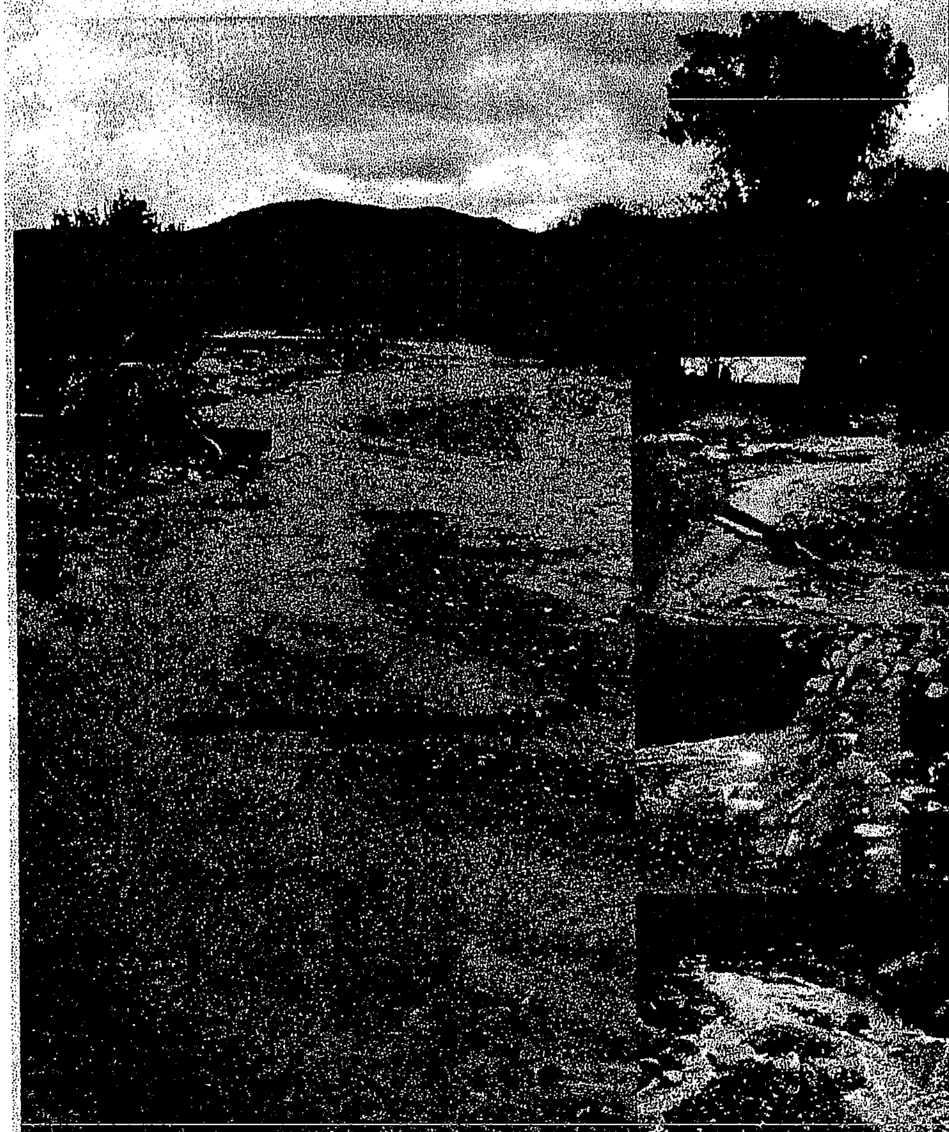
# Effect of Increases in Peak Flows and Imperviousness on the Morphology of Southern California Streams

Technical Report 450
April 2005



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# EFFECT OF INCREASES IN PEAK FLOWS AND IMPERVIOUSNESS ON THE MORPHOLOGY OF SOUTHERN CALIFORNIA STREAMS

A report from the Stormwater Monitoring Coalition

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Technical Report #450

## EXECUTIVE SUMMARY

Urbanization in southern California has resulted in direct and indirect effects on natural stream courses that have altered their physical and biological character. Development typically increases impervious surfaces on formerly undeveloped (or less developed) landscapes and reduces the capacity of remaining pervious surfaces to capture and infiltrate rainfall. The result is that as a watershed develops, a larger percentage of rainfall becomes runoff during any given storm. In addition, runoff reaches the stream channel much more efficiently, so that the peak discharge rates for floods are higher for an equivalent rainfall than they were prior to development. This process has been termed *hydromodification*.

Although the effects of increased impervious cover on stream flow have been well documented (Bledsoe, 2001; Booth, 1990; 1991; MacRae, 1992; 1993; 1996), the majority of past studies have focused on perennial streams. Until recently, few comparable studies have evaluated the impacts of urbanization on ephemeral or intermittent streams of arid or semi-arid climates. This had made it difficult to effectively manage stormwater impacts on southern California's natural streams. In response, the Stormwater Monitoring Coalition (SMC) conducted this study to assess the relationship between stream erosion and urbanization. It is anticipated that the results of this study will be useful in developing peak flow criteria for Los Angeles County as well as future stormwater regulations or management strategies.

The goal of this study is to assess relationships between stream channel type and resistance that will allow prediction of channel response under changed conditions associated with increased impervious cover. The specific study objectives are to:

- Establish a stream channel classification system for southern California streams;
- Assess stream channel response to watershed change, and attempt to develop deterministic or predictive relationships between changes in impervious cover and stream channel enlargement; and
- Provide a conceptual model of stream channel behavior that will form the basis for future development of a numeric model.

The intent of this study was to use multiple watersheds (each containing a single site) studied in broad scope rather than a single watershed (with many sites) studied in great detail. Consequently a total of 11 separate sites were selected in 8 distinct watersheds (Table ES-1).

Table ES-1 **Study Site List**

| Site No. | Site Name | CDA ($mi^2$) | Major Watershed | Type of Site | County |
|---|---|---|---|---|---|
| 1 | Topanga Creek | 18.07 | Santa Monica Bay | Control Site | Los Angeles |
| 3u | Hasley Canyon | 1.55 | Santa Clara River | Control Site | Los Angeles |
| 3d | Hasley Canyon | 1.66 | Santa Clara River | Developed Site | Los Angeles |
| 4u | Plum Canyon | 2.23 | Santa Clara River | Developed Site | Los Angeles |
| 4d | Plum Canyon | 2.40 | Santa Clara River | Developed Site | Los Angeles |
| 7u | Borrego Canyon | 2.27 | San Diego Creek | Developed Site | Orange |
| 7d | Borrego Canyon | 3.06 | San Diego Creek | Developed Site | Orange |
| 9 | Serrano Creek | 2.64 | San Diego Creek | Developed Site | Orange |
| 10 | Santiago Creek | 12.36 | Santa Ana River | Control Site | Orange |
| 23 | Dry Canyon | 1.22 | Calleguas Creek | Control Site | Ventura |
| 27 | Hicks Canyon | 1.33 | San Diego Creek | Control Site | Orange |

CDA = catchment drainage area

The study approach was to evaluate the changes in stream channel configuration over time and compare them to the changes in total basin impervious cover (TIMP) over the same time period. Data collection occurred in two phases. In the first phase background and historic information was gathered on each site and its contributing drainage area. In the second phase detailed field data was collected on the geomorphic condition of each study reach. The combinations of historic and contemporary data were used to develop predictive relationships between changes in impervious cover and channel form.

This study resulted in the following general conclusions regarding the relationship between impervious cover and stream channel form for ephemeral streams in southern California:

1. **Southern California streams exhibit deterministic relationships between bankfull discharge ($Q_{bfl}$), and measures of channel geometry such as cross section area ($A_{bfl}$).** Of the field measures calculated, the greatest consistency in relationship to the discharge rate at the bankfull stage, also termed the *Dominant Discharge* ($Q_{bfl}$), was with the channel cross-sectional area ($A_{bfl}$). Dominant Discharge exhibited a clear, predictable (or deterministic) relationship with features of channel geometry, such as channel width and cross-section area, i.e. as discharge increases, predictable increases in channel size are observed. An example of this deterministic relationship is shown in Figure ES-1, which indicates that the initial channel response to increases in discharge is to widen; however, with increasing discharge, the rate of channel widening decreases and downcutting is the predominant response.

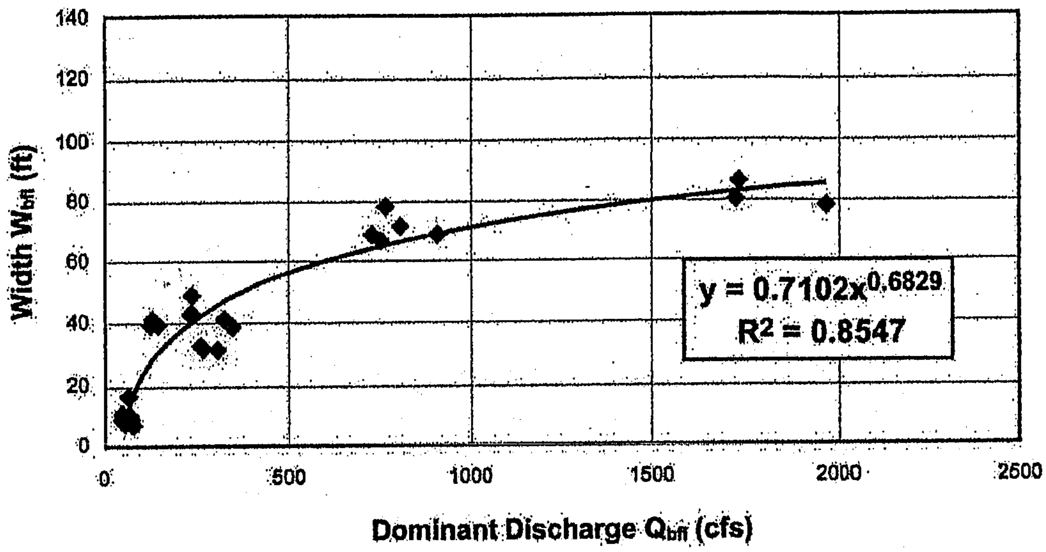


**Figure ES-1: Relationship of Dominant Discharge to Channel Width**

2. **The ephemeral/intermittent streams in southern California appear to be more sensitive to changes in TIMP than streams in other areas.** Stream channel response can be represented using an *enlargement curve*, which relates the percent of impervious cover (TIMP) to a change in cross-sectional area (Figure ES-2). The data for southern California streams forms a relationship very similar in shape to the enlargement curves developed for other North American streams. However, the curve for southern California streams is above the general curve for streams in other climates. This suggests that a specific enlargement ratio is produced at a lower value of impervious surface area in southern California than in other parts of North America. Specifically, the estimated threshold of response is approximately 2-3% TIMP, as compared to 7-10% for other portions of the U.S. It is important to note that this conclusion applies specifically to streams with a catchment drainage area less than $5 mi^2$.

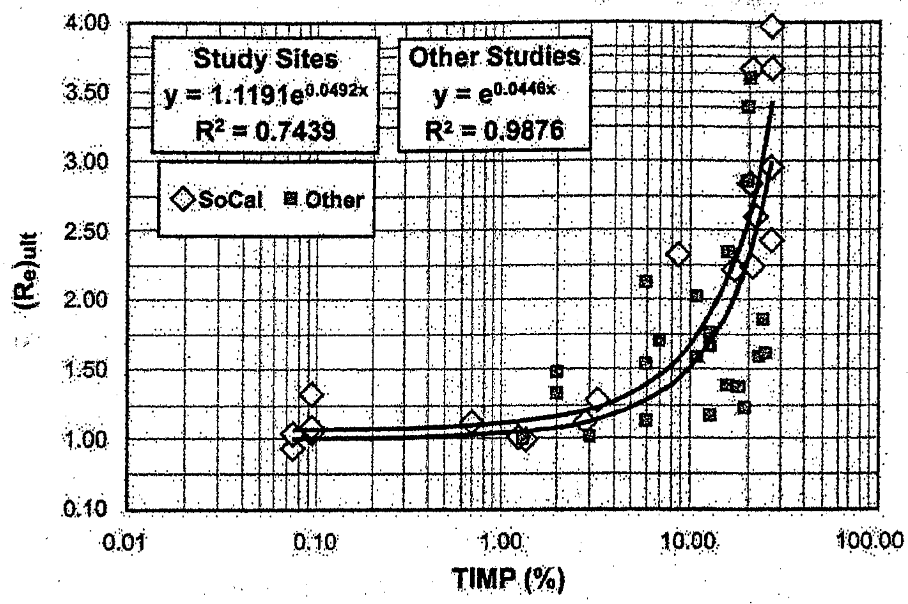


**Figure ES-2. Enlargement Curve for Southern California.**

*Upper curve and data points are for southern California channels in the current study. Lower curve is based on data from other locations in North America.*

3. **There is a natural background level of channel degradation that is occurring in all stream channels studied, even in the absence of development within the drainage area.** A minimal rate of change in channel bottom elevation was observed in all sites, regardless of whether the watershed has experienced an increase in impervious cover. Control sites exhibited a state of dynamic equilibrium where downcutting was observed, but channel morphology did not change appreciably over time. In contrast, the developed sites exhibited instability, where one or more measures of channel morphology changed over time. In addition, the rate of change in downcutting was greater in the developed sites than in the control sites. For example, at the Dry Canyon control site downcutting was estimated to be 0.7 ft/yr, while the rate at the developing Plum Canyon site was estimated to be 1.7 ft/yr. These results demonstrate poor channel resistance to increased flow in all stream channels except those subject to bedrock control, such as Topanga Creek.

4. **Streams are sensitive to both peak discharge and duration of discharge.** The ephemeral and intermittent streams investigated in this study appear to be highly sensitive to changes in flow rates associated with increased impervious cover. Additionally, they appear to have a low resistance to erosion, which results in increased susceptibility to channel enlargement in response to increases in the duration of high flows.

The predictive relationships established in this study can be used to evaluate potential effects of proposed development on the stability of natural streams. There are ranges of strategies that can be used to help reduce the potential effects of increased TIMP. However, the selection of a management strategy is dependent upon the extent to which a stream channel has been impacted by development within the watershed, the nature of the stream channel reach under consideration, and the anticipated future watershed conditions (i.e. expected increases in TIMP). Three general strategies should be considered when attempting to manage increases in peak flow:

1. **Limit Impervious Area.** Although the focus of this study was necessarily on TIMP, disconnecting impervious areas from the drainage network and adjacent impervious areas is a key approach to protecting channel stability. Utilizing this strategy can make it practical to keep the effective impervious cover (i.e. the amount hydrologically connected to the stream) equal to or less than the identified threshold of 2-3%.

2. **Control Runoff.** Hydrograph matching is not recommended for a single "design" storm with a specific return period, but rather for a range of return periods from 1 year to 10 years. Accomplishing such hydrograph matching will be challenging, and undoubtedly require a combination of techniques to prevent (retain), as well as to delay or attenuate (detain) runoff and/or stream flow.

3. **Stream Channel Movement.** Allow the greatest freedom possible for "natural stream channel" activity. This includes establishing buffer zones and maintaining setbacks to allow for channel movement and adjustment to changes in energy (associated with runoff). However, where in-stream controls are required consider all potential management options.

It is important to keep in mind that the choice of a management approach or approaches should be dictated by the strategies that are appropriate given the conditions of each stream reach and its contributing watershed. Consequently a suite of management approaches may need to be applied to provide a comprehensive solution to managing potential increases in runoff due to land use change.

Stream channels respond to changes in basin imperviousness in complex ways, and specific responses will vary based on the characteristics of the stream and watershed. An exhaustive analysis of these issues was beyond the scope of this study; nevertheless, the present study represents an important first step in understanding the response of ephemeral streams to increases in impervious cover.

## ACKNOWLEDGEMENTS

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# 1.0 INTRODUCTION

The southern California region is expected to experience significant urbanization over the next several decades that has the potential to have significant impact on the many ephemeral or intermittent streams of this arid to semi-arid region. In response to this concern, the 2001 Los Angeles County Municipal Stormwater Permit calls for a study to help develop numeric criteria to prevent or minimize erosion of natural stream channels and banks associated with urbanization.

Working through the Stormwater Monitoring Coalition (SMC), the Southern California Coastal Water Research Project (SCCWRP) has been designated as the facilitator for studies to assess the relationship between stream erosion and urbanization. It is anticipated that the results of this study will be useful in developing peak flow criteria for Los Angeles County as well as future stormwater regulations. Earth Tech, Inc. has been retained to conduct this study to relate measurable urban/suburban development within a watershed to observable changes in stream-channel morphology (including width, depth, cross-sectional area, and plan-form shape) in the southern California region.

## 1.1 Project Background

The process of urbanization alters many aspects of a landscape and often results in the emplacement of structures and infrastructure. One of the primary changes that has the potential to affect stream courses is alteration of watershed hydrology. Development increases impervious surfaces on formerly undeveloped (or less developed) landscapes and reduces the capacity of remaining pervious surfaces to capture and infiltrate rainfall. The result is that as a watershed develops, a larger percentage of rainfall becomes runoff during any given storm. In addition, runoff reaches the stream channel much more efficiently, so that the peak discharge rates for floods are higher for an equivalent rainfall than they were prior to development. This has been well documented since the early research by Hammer (1972) and Hollis (1975), through the recent efforts of Bledsoe (2001), Booth (1990, 1991), and MacRae (1992, 1993, 1996). Changes in runoff and flow have also been shown to result in impacts on aquatic habitat and species (Benke, et al. 1981, Booth and Jackson 1997, Garie and McIntosh 1986, Jones and Clark 1987, and Pedersen and Perkins 1986).

Although the effects of increased impervious cover on stream flow have been well documented, the majority of past studies have focused on perennial streams. Few comparable studies have evaluated the impacts of urbanization on streams of arid or semi-arid climates where most of the smaller streams are ephemeral or intermittent. Ephemeral streams are defined as those that flow only in direct response to a rainfall event, and (particularly in southern California) are otherwise dry for most of the year. Intermittent streams will have base flow for some of the period between rainfall events, but will also have dry periods throughout the year. Perennial streams will flow throughout the year, having enough base flow to maintain water in the stream channel even during the long months of the dry season.

Two recent projects in California have begun to investigate effects of increased peak flow on arid streams that were either formerly ephemeral (Thompson Creek in Santa Clara County) or presently and historically ephemeral (Arroyo Simi in Ventura County). In each case, reports prepared for these projects summarized the relevant literature and noted the sparseness of work on streams in arid or semi-arid climates. GeoSyntec (2002) provides a substantial review of the literature on this topic, and AQUA TERRA (2004) contributes additional references not covered in the more extensive GeoSyntec (2002) literature review. Of the 123 papers, reports, or books reviewed between these two references, only one citation was noted specifically for considering and evaluating ephemeral streams (Caraco 2000). This emphasizes the lack of reference material available for assessing ephemeral or intermittent streams in dry climates.

There are additional classic (Graf 1987) and recent (Tooth 2000, and Bull and Kirkby 2002) works on stream processes in arid areas not cited by the recent California projects. However, these additional publications do not focus on impacts from increased imperviousness. Therefore, the limited nature of applicable research is particularly problematic for the relatively steep arid and semi-arid streams typically found in southern California, which may have different bed and bank properties than streams in other regions. The lack of research into the impacts of urbanization on ephemeral and intermittent streams also makes it difficult to manage stormwater impacts on natural streams effectively in southern California or other parts of the southwest. Furthermore, the current, rapid pace of urbanization in foothill areas of the study region emphasizes the importance of understanding the relationship between changes in the hydrologic and hydraulic processes of these systems and the resultant change in stability of the streams in arid watersheds. Such an understanding is urgently needed to help managers make informed decisions regarding strategies to protect these streams.

The present study is another step toward understanding the responsiveness of ephemeral stream channels to changes in hydrology (i.e. evaluating their resistance to expected changes in the flow peaks and duration). The approach adopted here differs from the two recent efforts in California to evaluate the impacts of urbanization. AQUA TERRA (2004) used a modeling approach with field verification to evaluate a single watershed using data from six stream channel monitoring points. GeoSyntec (2003), also used multiple stream channel data collection points within a single watershed to evaluate stream channel response to development. The present study evaluated stream channel study sites in multiple, small watersheds from a larger geographic area that includes Los Angeles, Orange and Ventura counties in order to begin developing a regional understanding of the relationship between increased impervious cover and stream channel stability.

## 1.2 Study Objectives

The primary objective of this study was to find relationships between stream channel type and resistance that would allow prediction of channel response under changed conditions associated with increased impervious cover. Ultimately this effort will contribute to the establishment of stormwater management criteria to help minimize the impacts to stream channels from the conversion of undeveloped (or less developed) areas to residential, commercial, or other intensive land uses.

The study was structured to address specific problems expressed in terms of urbanizing systems (Table 1-1). Although solutions to these problems may not be attainable through this study, they are presented as a desirable outcome of this type of research. More tenable study goals are provided as reasonable expected results of this project. Finally, several viable approaches applied by this project are presented to indicate how the study addressed the stated problems in order to reach the stated study goals.

**Table 1-1. Project Structure**

| Problems | Approaches | Study Goals |
| --- | --- | --- |
| 1. Understand stream channel response to urbanization in southern California streams.<br>2. Isolate the effects of urbanization on stream channel response.<br>3. Identify geomorphic thresholds for southern California streams.<br>4. Understand the effectiveness of mitigation strategies.<br>5. Establish a model or procedure to extrapolate relationships based on case studies. | 1. Use data obtained from the study sites to establish a stream channel classification system for southern California.<br>2. Use stream channel type to discriminate among the quantifiable impacts to stream channel morphology.<br>3. Establish a procedure to assess significance of morphological impacts. | 1. Evaluate the impact of urbanization on stream morphology in natural [illegible] general stream-channel systems in southern California.<br>2. Develop cause and effect relations between stream channel morphology change and urbanization.<br>3. Review potential BMP implementation.<br>4. Recommend possible applications of this study's findings to other streams and watersheds in southern California. |

Since this was an empirical study, it required several stream channel sites that were selected from within a six-county region in southern California. The investigation looked at historical changes in stream channel configuration relative to historical changes in land use. The intent, therefore, was to use multiple watersheds (each containing a single site) studied in broad scope rather than a single watershed (with many sites) studied in great detail. Consequently a total of 11 separate sites were selected in 8 distinct watersheds. The locations of these watersheds are regional, and range from northwestern Los Angeles County through southern Ventura County, and down to central Orange County. The evaluations performed should allow a greater range of site conditions to be evaluated than they would for a single watershed, and ultimately provide results with broader applicability in the southern California region. There is a great need for additional research in this geographic area on the impacts from urbanization, and this need is for both focused (single watershed) and regional (multiple watersheds) investigations. The two recent California studies (AQUA TERRA 2004 and GeoSyntec 2004) were focused studies. The present study is the first regional investigation of ephemeral stream channel response to urbanization.

The objectives of this study, which were needed in establishing the relationship sought by the primary study goal, include the following:

- Create a classification system to generalize responses of different types of stream channels,
- Evaluate stream channel response to watershed change, and
- Attempt to provide a conceptual model of stream channel behavior.

While the results of the current study are only directly applicable to the sites included in this study, the use of a classification system similar to the one proposed here (see Section 3) holds promise for eventually broadening this applicability and allowing extrapolation of results to other similar stream types. Understanding such relationships could be an important part of future watershed and stormwater management by identifying stream channel reaches that are most susceptible to change. Toward this end, Section 4 of this report provides some recommendations for additional research needs to provide a broader scientific basis for the classification of stream channels in all six counties of the study region and their applicability to different development scenarios.

# 2. DATA COLLECTION METHODS

This study employed a stepwise stream evaluation protocol previously applied at a number of sites throughout North America, and developed partly from research conducted worldwide (Table 2-1). This project evaluated the applicability of this protocol to the semi-arid southern California region. Specifically, the study tested the comparability of relationships derived from southern California streams to data collected in other areas encompassing more diverse hydrologic settings. If the two data sets are comparable, the larger data set can be used to augment the relatively modest data expected from this study; thereby strengthening the reliability of the analysis based on local conditions.

## 2.1 Evaluation Process

The overall protocol includes eleven steps, but only steps 1 through 5, 7, and 8 have been employed in this study, as this study has been broadly applied to sites in southern California rather than being applied to a single watershed with multiple stream or river channel sites. Each step of the process and a brief summary of its application to this study are provided below. The remaining sections of this report provide background information on the study sites and evaluations performed for the application of this protocol. Detailed field and analytical data are contained in the appendices to this report.

**Table 2-1. Eleven-Step Protocol**
*The Protocol, as applied in this study pertains to the geomorphic component of stream channel investigations.*

| ID | Name | Question |
|---|---|---|
| STEP 1 | Study Objectives | What is the nature and degree of the perceived problem? |
| STEP 2 | Past Stream channel | What was the form of the historic stream channel? |
| STEP 3 | Expected Disturbances | What future disturbance is likely to occur? |
| STEP 4 | Present Stream channel | What is the stream channel like today? |
| STEP 5 | Future Stream channel | What will the stream channel look like in the future? |
| STEP 6 | Accept/Reject Future | Is the future stream channel form desirable, acceptable or unacceptable? |
| STEP 7 | Disturbance Control | Can the perturbations be controlled through watershed planning? |
| STEP 8 | Channel Works | Are instream works required, desirable, feasible and practical? |
| STEP 9 | River Management | What is the preferred river corridor management plan? |
| STEP 10 | Engineering Design | What does the detailed design look like? |
| STEP 11 | Implementation | How will the plan be implemented? |

**Study Objectives.** The first step of the protocol is to establish study objectives by defining the problems to be solved, establishing goals for solving these problems, and defining an assessment approach for determining when the goals are reached. For this study, the objectives have been articulated previously in Section 1.2, Study Objectives.

**Past Stream Channel.** Previously surveyed cross sections were available for each of the study sites, including at least one at every stream channel reach. These cross sections are an important key to evaluating how stream channel morphology differed in the past from its present-day form. The differences in stream channel geometry between past sections and present sections were evaluated for every site. The results of this evaluation are used as a basis for both the stream channel classification system and the stream channel response evaluation discussed in Section 3 of this Technical Report.

**Expected Disturbances.** This study is focused entirely on expected disturbances related to land use changes within the watersheds of these sites. Therefore, evaluation of expected disturbances is centered on changes in energy and erosion potential at these stream reaches.

**Present Stream Channel.** The present stream channel configurations are very clearly understood at all of the sites through the diagnostic surveys performed in May 2004. Each stream channel reach had from three to six cross sections surveyed, with characterizations made of the topography and the composition of bed and bank materials. In addition, a longitudinal profile was also surveyed that tied all of the cross sections together spatially and geometrically.

**Future Stream Channel.** Evaluation of the historical changes in stream channel morphology, combined with the data on bed and bank material composition, and bank cohesion, allowed an assessment of the potential for additional adjustment in stream channel morphology at each of the study reaches.

**Accept/Reject Expected Future.** If the purpose of this study had been stormwater management for a specific watershed, then the intent of this step would be applicable to the current discussion. However, because this effort is attempting to characterize a broad range of stream channels and assess their thresholds for stream channel change (most specifically enlargement), accepting or rejecting change is not required.

**Disturbance Control.** This study attempts to provide a generic assessment of the effectiveness of different classes of stormwater management measures, and when they can be appropriate to use in controlling the expected stream channel change resulting from urbanization.

**Channel Works (BMPs).** This project also considers the need for, and appropriate use of, in-channel management practices and under what conditions they might be appropriate.

## 2.2 Site Selection

The general goals in site selection were to find stream channels that would be representative of stream channel types across the region. In addition, candidate sites needed to have available historic information on the stream channel and the watershed. Finally, the selected watersheds must have been subject to some degree of development over the period for which information is available.

A detailed discussion of the logic behind the site selection process, and the guidelines applied while selecting the sites used in the study, can be found in the Work Plan prepared for this effort (Earth Tech, 2004). However, a brief summary of each guideline is presented below. A brief description of the sites selected and key background information on each site is presented in Sections 3.

- **Selection Guideline 1. Small Watershed Size.** The target drainage area for selected study sites/reaches was between 1 and 5 square miles, depending upon the degree of impervious cover.

- **Selection Guideline 2. Shear Stress Dominated.** The selected stream channel sites needed to have well-formed morphological characteristics that could be readily distinguished and surveyed using traditional geomorphic and engineering study techniques. Ideally, the stream channel system would be approaching a metastable position and shear stress processes are the dominant channel-forming mechanism.

- **Selection Guideline 3. Natural Channel.** The stream channels were to be primarily undisturbed by direct human activity (as well as could be determined) during the surveyed period. This included such activity as channel straightening, channel enlargement, bank protection or stabilization, upstream or downstream hydraulic control devices, and sediment trapping or containment structures. The length of the undisturbed stream channel needed to be greater than the minimum survey length of 1 to 2 meander wavelengths or the equivalent of 10 to 20 bankfull stream channel widths.

- **Selection Guideline 4. Development.** The watershed areas of the sites had to contain some level of urban (or suburban) development. Preferably at least 5 to 10 percent of the land area within the watershed should be in urban, suburban, commercial, or industrial land use categories.
- **Selection Guideline 5. Historic Cross Sections.** It was absolutely critical that each of the sites has previous stream channel cross-section surveys available for comparison. Ideally, these cross sections would be for one or more time periods prior to, and during the development period. Preferably the surveys would be from a time when a smaller percentage of the watershed was developed than it is currently.
- **Selection Guideline 6. Streamflow Data.** Sites were sought with stream flow data available in or near the study reach. Acceptable data was from actual flow measurements, modeled flow values, estimated peak discharges for specific recurrence intervals, or regional relationships. In the absence of such data, some idea of the number of days in a year that the stream channel contains flowing water was sought.
- **Selection Guideline 7. Aerial Photos.** Although not required, paired, stereographic aerial photographs at a useable scale (e.g., 1:10,000 or better) were sought for one or more historic periods.
- **Selection Guideline 8. Topographic Maps.** A study reach needed maps with a useable scale and contour interval (ideally 1 inch = 50 feet, to 1 inch = 100 feet, and a contour interval of 1 foot).
- **Selection Guideline 9. Geotechnical Data.** The availability of the results of geotechnical investigations that characterized materials similar to the stream channel bank and bed materials for a reach was considered very helpful in the site selection process.

The site selection process was a two-phase effort of (1) identifying potential (or "candidate") sites and (2) picking a subset of these sites for inclusion in the investigation. The process included contacting federal, state, county, and local government agency personnel, faculty members at local universities, and staff at local non-profit organizations to seek recommendations for candidate sites that generally appeared to meet the selection guidelines. The identified candidate sites are shown in Figure 2-1, as well as the final selected sites for the study. Details on the selected sites are given in Section 3.0, including location, topography, local geology, and other salient information.

## 2.3 Data Collection

Two phases of data collection were conducted for each of the eleven selected study sites. The first phase consisted of collecting background and historic information on each site and its contributing drainage area. The second phase consisted of collecting intensive field data on the geomorphic condition of each study reach. These two phases are described in detail in sections 2.3.1 and 2.3.2 below.

The historic data gathered for this study included the following types:

- Land use maps and/or digital files marking a specific land use coverage at a specific point in time.
- Surveyed cross sections (of distance and elevation) previously measured at each of the study sites.
- Precipitation records for rain gauges close to the watershed areas of the study sites; primarily annual amounts for the period of record.
- Stream flow measurements at local USGS (or other) stream gages; mostly annual peak flows for the period of record.
- Aerial photographs covering a range of times over the watershed area.

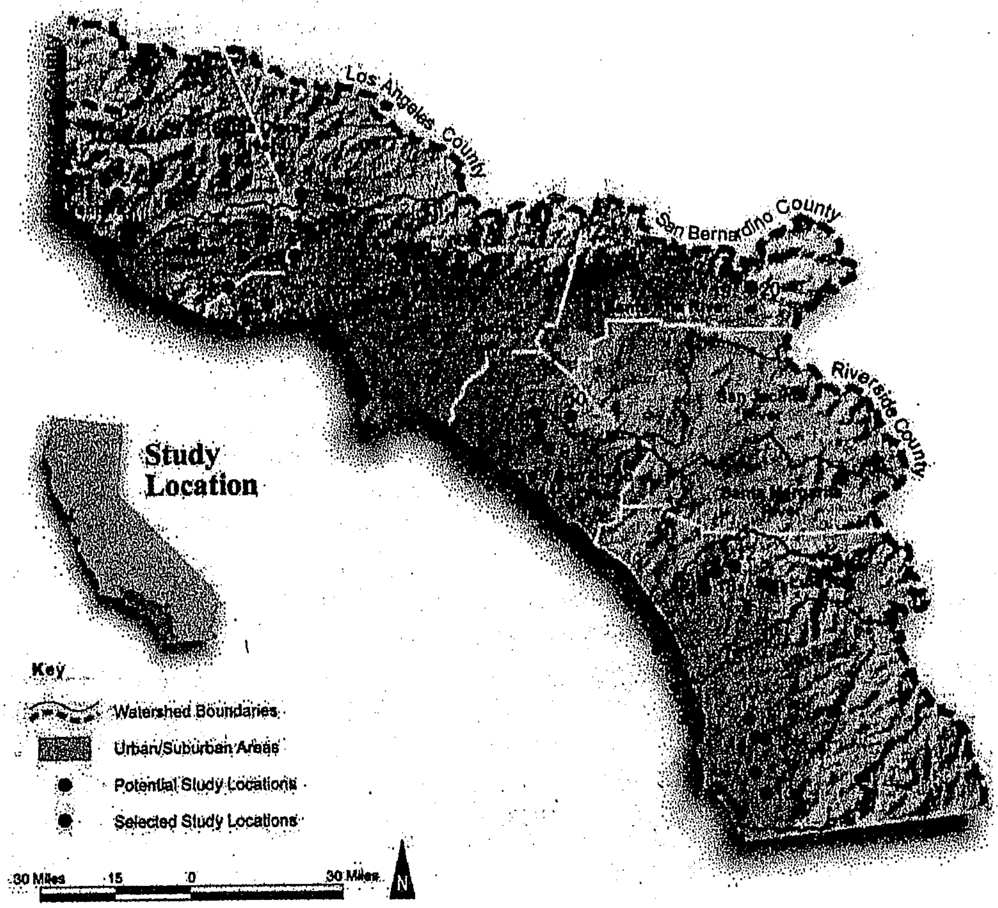



**Figure 2-1. Study Sites**

Map of study area showing the locations of potential study sites. See Table 1-1 for identification of, and additional information about, the selected study sites.

*(Includes all candidates sites.)*

- Evaporation (or evapotranspiration) records or approximate amounts for the watershed of the modeled reach.
- Satellite imagery and interpretation for impervious areas in the Hasley Canyon and Plum Canyon watersheds.

The current data was collected during two weeks of field work in May 2004. The specific types of field data collected at each of the stream channel reaches selected for this study include:

- Total-station surveys of the entire study reach that included stream channel cross sections (especially at locations of the previously surveyed cross sections), longitudinal profiles of the stream channel, and other points of interest tied to the geomorphic mapping.
- Geomorphic mapping of the stream channel reach, including up to, and slightly beyond the perceived "bankfull" channel configuration.
- Pebble counts and/or sieve analyses at multiple points across the stream channel to characterize bed materials.
- Sieve analyses and Torvane® shear stress meter readings to characterize bank material sizes and cohesion of both right and left banks.
- Rapid geomorphic assessment of each study reach.

### 2.3.1 Historic Data

Sources for the historic data are summarized below. These data generally required some amount of processing to make them consistent with the other data sources, and useable with the field-generated data from the current study.

**Land Use.** Land use data were used as a surrogate for impervious surface area within the watersheds. Land use/impervious cover data came from three primary sources (Table 2-2). The basic land use data came from detailed maps prepared for the Southern California Association of Governments (SCAG) for the years 1990, 1993, and 2001. Older land use data came from aerial photos and interpreted land use maps for the Serrano Creek and Borrego Canyon sites made available by Felicia Federico of UCLA. Data from DigitalGlobe was used to supplement the land use mapping for Hasley and Plum canyons. It consisted of digital orthoimagery collected with the QuickBird® satellite, which was used to supplement the SCAG land use maps. The DigitalGlobe imagery of Hasley Canyon was taken on 23-July-2002, while the imagery for Plum Canyon was taken on 22-March-2003.

**Cross Sections.** Previously surveyed cross sections came from six primary sources (Table 2-3). Most data were for multiple sections surveyed one or more years apart. The exceptions were Topanga Creek (one section, one survey time), Borrego Canyon (one section for each site, multiple survey times), and Santiago Creek (four sections, one survey time). Monuments used in the original survey, or other recoverable "surrogate" monuments were used to tie the current surveys to their historic cross section counterparts.

**Precipitation Records.** Rainfall records were sought for each watershed area to provide background information on relative hydrologic conditions for the period of land use change and the related adjustment in stream channel morphology (Table 2-4). Rainfall records were obtained for multiple weather stations near the watershed areas of the sites. The relative locations of the weather stations to the watersheds are shown in Figures 2-2 and 2-3.

**Table 2-2. Land Use/Impervious Cover Data**

| Site | | Source | Information |
|---|---|---|---|
| Site 1. | Topanga Creek | SCAG (2004). | Land use mapping with GIS layers for 1990, 1993, and 2001 data. |
| Site 3. | Hasley Canyon | SCAG (2004), DigitalGlobe (2004). | Land use mapping with GIS layers for 1990, 1993, and 2001 data; satellite imagery for 23-July-2002. |
| Site 4u. | Plum Canyon (upstream) | SCAG (2004), DigitalGlobe (2004). | Land use mapping with GIS layers for 1990, 1993, and 2001 data; satellite imagery for 22-March-2003. |
| Site 4d. | Plum Canyon (downstream) | SCAG (2004), DigitalGlobe (2004). | Land use mapping with GIS layers for 1990, 1993, and 2001 data; satellite imagery for 22-March-2003. |
| Site 7u. | Borrego Canyon (upstream) | SCAG (2004), Aerial Photos. | Land use mapping with GIS layers for 1990, 1993, and 2001 data; aerial photos for 1952, 1967, 1972, 1983 |
| Site 7d. | Borrego Canyon (downstream) | SCAG (2004) Aerial Photos. | Land use mapping with GIS layers for 1990, 1993, and 2001 data; aerial photos for 1952, 1967, 1972, 1983 |
| Site 9. | Serrano Creek | SCAG (2004) Aerial Photos and Interpretation (Federico 2003). | Land use mapping with GIS layers for 1990, 1993, and 2001 data; land use mapping for 1949, 1968, 1978, 1982, and 1997 |
| Site 10. | Santiago Creek | SCAG (2004). | Land use mapping with GIS layers for 1990, 1993, and 2001 data |
| Site 23. | Dry Canyon | SCAG (2004). | Land use mapping with GIS layers for 1990, 1993, and 2001 data |
| Site 27. | Hicks Canyon | SCAG (2004). | Land use mapping with GIS layers for 1990, 1993, and 2001 data |

**Stream Gage Records.** Although only two of the sites (Topanga Creek and Santiago Creek) have stream gages near the study reach, we have collected stream flow records from local gages for as many of the reaches as possible (Table 2-5). These gage records have been used to establish flow frequency relationships that are essential for estimating the recurrence interval (RI) of discharge values calculated for the study sites. The process involves prorating the calculated discharge values, by watershed area, to an equivalent discharge at a gage. The gage discharge is then used to estimate a RI with the established flow frequency relationship. Verification of these return period values made with the regional flood frequency relationships developed by the U. S. Geological Survey (Waananen and Crippen 1977).

**Table 2-3. Historic Cross Section Data**

| Site | | Source | Information |
|---|---|---|---|
| Site 1. | Topanga Creek | Rosi Dagit, Santa Monica Mountains Resource Conservation District. | Copy of field notes for original survey of cross section TS-1 performed in November 2000 by Orme, et al. (2002). |
| Site 3. | Hasley Canyon | Matt Yeager, Ph.D. candidate, University of California, Los Angeles. | Electronic file copies of surveys for cross sections HC-1, HC-2, HC-2.5, HC-3, HC-4, and HC-5 taken from October 2001 to April 2003. |
| Site 4u. | Plum Canyon (upstream) | Matt Yeager, Ph.D. candidate, University of California, Los Angeles. | Electronic file copies of surveys for cross sections PC-2, PC-2.75, PC-3, and PC-4 taken from October 2001 to April 2003. |
| Site 4d. | Plum Canyon (downstream) | Matt Yeager, Ph.D. candidate, University of California, Los Angeles. | Electronic file copies of surveys for cross sections PC-1, PC-2, and PC-2.5 taken from October 2001 to April 2003. |
| Site 7u. | Borrego Canyon (upstream) | Professor Stanley Trimble, Department of Geography, University of California, Los Angeles. | Copy of field notes for surveys of cross section (Range) 4A taken in September 1992, April 1993, December 1998, and February 2003. |
| Site 7d. | Borrego Canyon (downstream) | Professor Stanley Trimble, Department of Geography, University of California, Los Angeles. | Copy of field notes for surveys of cross section (Range) 4D taken in September 1992, April 1993, and February 2003. |
| Site 9. | Serrano Creek | Felicia Federico, Ph.D. candidate, University of California, Los Angeles. | Copy of field notes for surveys of cross section (Range) C taken in October 1997, and cross sections (Ranges) A2 and A4 taken in September 1991, and May 1993. |
| Site 10. | Santiago Creek | Jeff Agajanian, U. S. Geological Survey | Copy of field notes for surveys of cross sections XS-1, XS-2, XS-3, and XS-4 taken in April 1995. |
| Site 23. | Dry Canyon | Darla Wise, Ventura County Watershed Protection District | Electronic file copies of AutoCAD cross sections North, Middle, and South taken in October 2001, January 2002, and March 2003. |
| Site 27. | Hicks Canyon | Professor Stanley Trimble, Department of Geography, University of California, Los Angeles. | Copy of field notes for surveys of and cross sections (Ranges) A2 and A4 taken in September 1986, April 1992, and April 1993. |

**Table 2-4. Precipitation Data**

| Site | | Source | Information |
|---|---|---|---|
| Site 1. | Topanga Creek | Los Angeles County Department of Public Works (LA DPW) | LA Co. Stations 6 and 1194 |
| Site 3. | Hasley Canyon | LA DPW | LA Co. Stations 372, 801B, 1012B, 1262, and 1263 |
| Site 4u. | Plum Canyon (upstream) | LA DPW | LA Co. Stations 372, 801B, and 1262 |
| Site 4d. | Plum Canyon (downstream) | LA DPW | LA Co. Stations 372, 801B, and 1262 |
| Site 7u. | Borrego Canyon (upstream) | Orange County Resources and Development Management Department, Watershed and Coastal Resources Division (RDMD); California Irrigation Management Information System (CIMIS) | OC Stations 121, 165, 169, 173, 176 (annual and hourly), and 216; CIMIS Station #75 (hourly) |
| Site 7d. | Borrego Canyon (downstream) | RDMD and CIMIS. | OC Stations 121, 165, 169, 173, 176 (annual and hourly), and 216; CIMIS Station #75 (annual and hourly) |
| Site 9. | Serrano Creek | RDMD and CIMIS. | OC Stations 121, 165, 169, 173, 176, and 216 |
| Site 10. | Santiago Creek | RDMD and CIMIS. | OC Stations 121, 165, 169, 173, 176, and 216 |
| Site 23. | Dry Canyon | Ventura County Watershed Protection District (VC WPD) | Ventura Co. Stations 154, 193, and 196 |
| Site 27. | Hicks Canyon | RDMD and CIMIS. | OC Stations 121, 165, 169, 173, 176, and 216 |

**Table 2-5. Stream Gage Records**

| Agency | Site ID Number | Site Name | Elevation of Gage (ft.) | CDA ($mi^2$) | Years of Record |
|---|---|---|---|---|---|
| LA DPW | F54C-R | Topanga Creek above Mouth of Canyon | 265.6 | 16.0 | 63 |
| USGS | 11104000 | Topanga Creek near Topanga Beach, CA | 255.0 | 18.0 | 49 |
| USGS | 11047500 | Aliso Creek at El Toro | 440.0 | 7.9 | 50 |
| USGS | 11075800 | Santiago Creek at Modjeska | 1,210.0 | 13.0 | 42 |
| USGS | 11096500 | Little Tujunga Creek near San Fernando, CA | 1,068.4 | 21.1 | 46 |
| USGS | 11105850 | Arroyo Simi near Simi | 720.0 | 70.6 | 42 |

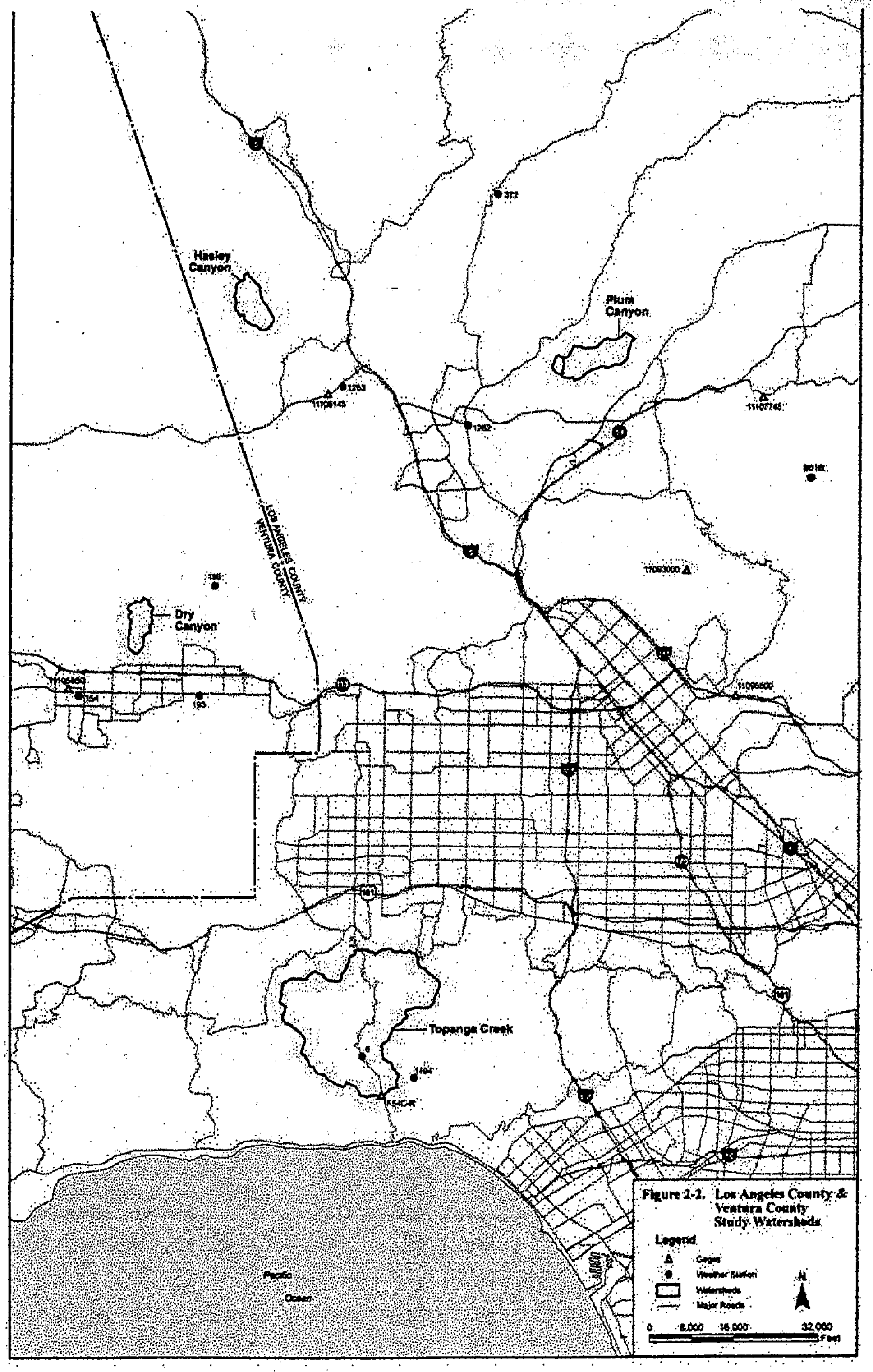



Figure 2-2. Los Angeles County and Ventura County Study Watersheds

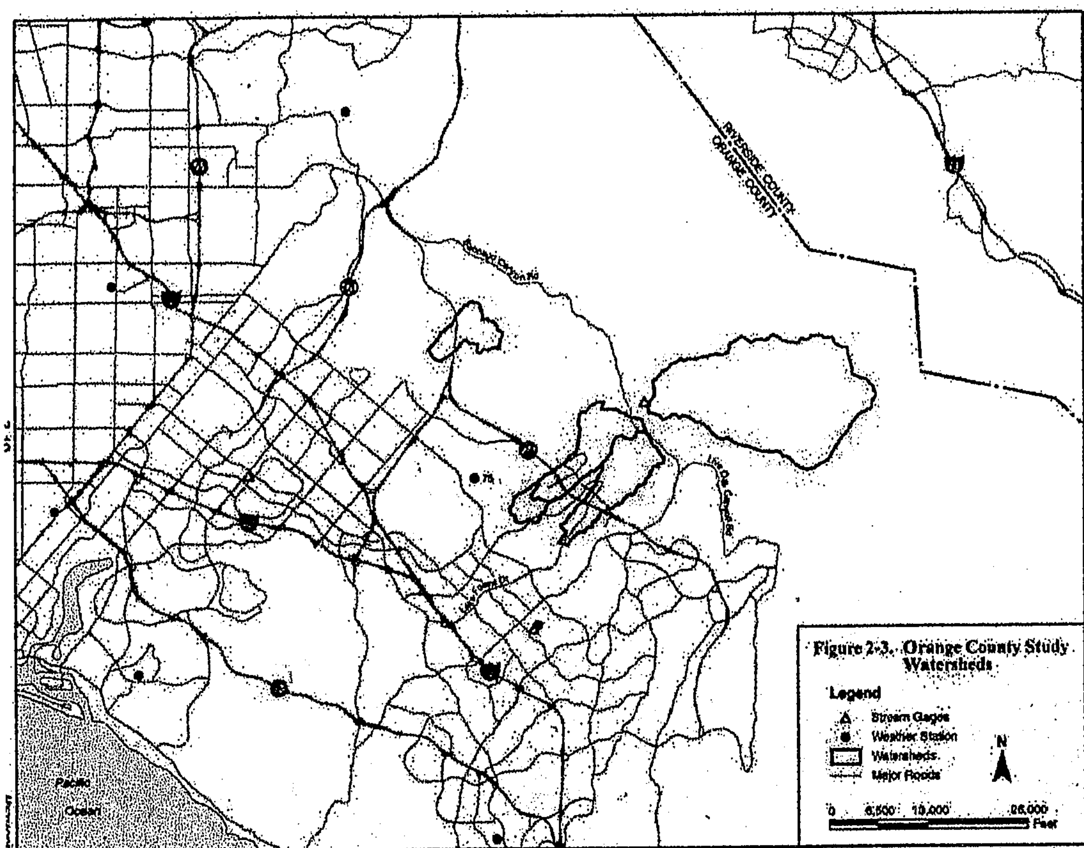



**Figure 2-3. Orange County Study Watersheds**

### 2.3.2 Field Data

Current conditions at each study site were evaluated through measurements and observations made during a two-week field program conducted from 3-May-2004 through 13-May-2004. A five- to seven-person field crew collected the data. The field procedures and data collection techniques are briefly described below. Data collected during this field program are provided in Appendix B.

**Topographic Surveys.** Distance and elevation readings were made using a Leica TPS700 Total Station surveying instrument. This instrument was capable of measuring distance, elevation difference, and declination from the instrument to a survey target, or prism. Readings were taken for specific stream channel features along the reach (thalweg, cut banks, bars chutes, etc.) as well as for the individual cross sections of interest. At least one cross section per site was termed the Master Section, and it coincided with the historic cross section, thus allowing comparison with the historic section(s) for that specific study reach. Generally the Master Section was the middle cross section in a series of three to five sections, and often had more detailed bed sediment data gathered, in addition to being the section used for evaluating historic changes at the site. Spacing of the cross sections were at distances approximately equal to 5 bankfull channel widths apart, for each of the 5 cross sections. Stream channel feature interpretations were also based on the geomorphic mapping prepared for the reach. Cross section surveys provide key data on stream channel morphology and capacity, which can be compared to historic values. Table 2-6 provides the details of which current cross sections match to the historic cross section(s) for each site. Longitudinal profile data, which also were measured during these topographic surveys, are important for deciphering current hydraulic conditions at these reaches, as well as estimating past or future conditions.

**Geomorphic Mapping.** Detailed mapping of geomorphic features was prepared for the reach at each study site using tape measure readings from a survey centerline that was established for the site during the survey. The centerline tape was turned and extended as needed to complete the full reach. Centerline points were included in the topographic surveys to help align and combine them with the synoptic geomorphic mapping, once both were completed. Specific geomorphic features were mapped that would aid in interpreting the current conditions in the study reach and help define what morphological changes had occurred.

**Bed Material.** Composition of bed material was characterized through a combination of pebble counts (Wolman 1954) and sieve analyses at a selected number of points across the bed at each surveyed cross section for all study sites.

**Bank Material.** Composition of the material in the stream channel banks was characterized through a combination of sieve analyses, detailed soil descriptions including standard field assessment of silt and clay fractions.

**Rapid Geomorphic Assessment.** In addition to the detailed synoptic mapping that was conducted, a quick assessment of the condition of each reach was made with a tool called the rapid geomorphic assessment (RGA; see Section 5.7 for additional details on the RGA).

**Table 2-6. Matching Cross Section Surveys**

| | | Historic Cross Section ID[1] | | | | | |
|---|---|---|---|---|---|---|---|
| **Site** | **Current Section[2]:** | **1** | **2** | **3** | **4** | **5** | **6[3]** |
| Site 1. | Topanga Creek | -- | TS-1 | -- | ns | ns | ns |
| Site 3u. | Hasley Canyon (upstream) | -- | -- | -- | HC-2 | ns | ns |
| Site 3d. | Hasley Canyon (downstream) | -- | HC-2.5 | -- | -- | ns | ns |
| Site 4u. | Plum Canyon (upstream) | -- | -- | -- | PC-3 | PC-4 | ns |
| Site 4d. | Plum Canyon (downstream) | -- | PC-1 | -- | -- | -- | ns |
| Site 7u. | Borrego Canyon (upstream) | -- | -- | Range 4A | -- | -- | ns |
| Site 7d. | Borrego Canyon (downstream) | -- | -- | Range 4D | -- | -- | ns |
| Site 9. | Serrano Creek | -- | -- | Range D | Range C | Range B2 | ns |
| Site 10. | Santiago Creek | XS-4 | XS-3 | XS-2 | XS-1 | -- | ns |
| Site 23. | Dry Canyon | -- | South | Middle | North | -- | na |
| Site 27. | Hicks Canyon | -- | Range A2 | -- | Range A4 | -- | Range A3 |

(1) Historic sections as identified by the source.

(2) Current section numbering starts at the downstream end of the reach. Unique section identification numbers have been given to each current section for the discussion and data presentation in Appendix C.

(3) Section 6 was surveyed only for Hicks Canyon, and that section was on a tributary, not the main stream channel.

ns Not a surveyed cross section in the current program.

# 3. STREAM CHANNEL STUDY SITES

The site selection effort covered a six-county region, including Los Angeles, Orange, Riverside, San Bernardino, San Diego, and Ventura counties. There were two general phases in the site selection process. Phase I was a screening process to identify candidate sites that generally appeared to meet the selection guidelines established for the project. Contacts were made either by networking referrals or targeting local agencies in the study region. The final candidate site list included a total of 27 stream channel locations in five of the six counties in the study region. No candidate sites were identified for Riverside County. Locations of all 27 candidate sites are shown in Figure 2-1. Phase II was a closer evaluation of the candidate sites to see how much data was available for each, and how well they met the specific selection guidelines. A total of 8 streams were selected for the study, after it was established that sufficient data was available for each. Two of these streams had multiple sections that proved distinct enough to be treated as separate sites. Therefore, sites 4 and 7 were divided into an upstream (4u and 7u) and a downstream (4d and 7d) site prior to field data collection. The selected sites are identified and key information provided on each in Table 3-1. After field data gathering was completed, it was concluded that Site 3 should also be treated as two separate sites. See the site description for Hasley Canyon in Section 3.1 for a discussion of this adjustment. Therefore, the final list of sites with data used in the evaluation presented in this report, included 11 sites in 8 different watersheds.

**Table 3-1. Study Site List**

| Site No. | Site Name | CDA ($mi^2$) | Major Watershed | Type of Site | County | Thomas Brother's Map Sheet No. |
|---|---|---|---|---|---|---|
| 1 | Topanga Creek | 18.07 | Santa Monica Bay | Control Site | Los Angeles | 630 |
| 3u | Hasley Canyon | 1.55 | Santa Clara River | Control Site | Los Angeles | 4459 |
| 3d | Hasley Canyon | 1.66 | Santa Clara River | Developed Site | Los Angeles | 4459 |
| 4u | Plum Canyon | 2.23 | Santa Clara River | Developed Site | Los Angeles | 4461 |
| 4d | Plum Canyon | 2.40 | Santa Clara River | Developed Site | Los Angeles | 4461 |
| 7u | Borrego Canyon | 2.27 | San Diego Creek | Developed Site | Orange | 861 |
| 7d | Borrego Canyon | 3.06 | San Diego Creek | Developed Site | Orange | 861 |
| 9 | Serrano Creek | 2.64 | San Diego Creek | Developed Site | Orange | 862 |
| 10 | Santiago Creek | 12.36 | Santa Ana River | Control Site | Orange | 832 |
| 23 | Dry Canyon | 1.22 | Calleguas Creek | Control Site | Ventura | 478 |
| 27 | Hicks Canyon | 1.33 | San Diego Creek | Control Site | Orange | 831 |

CDA = catchment drainage area

### 3.1 Study Site Streams

The stream channel study sites used in this investigation, with two exceptions, were formed in medium to coarse alluvial materials (sands and gravels). Topanga Creek and Serrano Creek were the exceptions, both being influenced by bedrock. The larger channels formed in alluvial materials have similar wide, shallow shapes (width to depth ratios greater than 20). The smaller watersheds, bedrock channels, and the control sites all have narrower and deeper channels (width to depth ratios smaller than 20).

**Topanga Creek.** Topanga Creek is located in western Los Angeles County between Highway 101 and the Pacific Ocean. The creek empties directly into Santa Monica Bay between Pacific Palisades and Malibu. The long axis of its watershed is oriented in a north-south direction and much of the watershed is in the Santa Monica Mountains. The watershed has some development in the northernmost part in the Glenview area and also in the central part of the watershed in Fernwood. The study site is located along Highway 27 (Topanga Canyon Boulevard), approximately halfway between Highway 101 and the Pacific Coast Highway. Gage records for this watershed show that it should be considered a perennial stream. Only 6 years in a 68-year record showed a minimum flow of zero.
Topanga Creek has outcrops of resistant volcanic bedrock in or near the channel in the study reach. There are also deposits of very coarse alluvial material, ranging from sand and silt to boulder sizes, in the valley bottom. The alluvium forms a flood plain with an atypical alluvial surface and rugged channel banks.

**Hasley Canyon.** Hasley Canyon is situated in northwest Los Angeles County west of Interstate 5, north of State Route 126, and between Lake Piru and Castaic Lake. The watershed trends from the northwest to the southeast. Development is occurring in the watershed adjacent to and upstream from the study site. Hasley Canyon is a tributary to Castaic Creek and is situated about 1.4 miles upstream from Castaic Creek's confluence with the Santa Clara River. The stream channel at this site is considered ephemeral, although there is a tributary entering from the west that had a small flow coming from the new large-lot residential development across Hasley Canyon Road. Evaluation of the data for Hasley Canyon demonstrated distinctly different changes at the upstream cross section (#4) compared to the other sections (#1, #2, and #3). It was concluded that a tributary to the main channel joining between section #3 and #4 affected only the lower sections (#1, #2, and #3). Furthermore, the watershed of this tributary includes all of the recently developed land (i.e. all of the increased total impervious surface area (TIMP)). As a result, the Hasley Canyon site has been divided into two sites; an upstream site (section #4) and a downstream site (sections #1, #2, and #3).

The Hasley Canyon channel is formed in a finer grained alluvium in the channel and has a more cohesive channel bank than most of these sites. In addition, there is an obvious enlargement and slight incision of the channel downstream from the tributary channel that drains the adjacent housing development.

**Plum Canyon.** Plum Canyon is located northeast of Santa Clarita in the Canyon Country of northern Los Angeles County. The watershed is a tributary of Bouquet Canyon, which empties into the Santa Clara River near the town of Saugus. The watershed is a northeast to southwest trending basin that is moderately developed in the lower portion and undergoing development in the upper portions. Two study reaches were used on Plum Canyon as sites, separated by a distance of more than 500 feet. Both sites are considered ephemeral stream channels, and both were dry in May 2004 during field data collection.
Plum Canyon, the stream channels of both the upstream and downstream sites, are formed in coarse materials (sands and gravels) and have wide, shallow channel shapes. These are among the steeper sites, both averaging more than a 2% gradient. Upstream from both sites is a major valley fill that has accounted for most of the new development within the watershed, extending up to the crossing of the Plum Canyon/Whites Canyon Road. In the early to mid 1990s a box culvert (twin 8' x 8' cells approximately 200' long) was installed to carry stream flow from Plum Canyon under the road. An extension of that conveyance (in the form of a single, 10-foot diameter, round concrete pipe) was installed

within the past five years to allow the placement of the valley fill. The outlet of this concrete pipe lies at least 1,500 feet upstream (linear channel distance) from the most upstream channel. This is well beyond the selection guideline of 10-20 bankfull widths (approximately 580 feet to 1,160 feet based on an average bankfull width of 58 feet for the upstream Plum Canyon site).

**Borrego Canyon Wash.** Borrego Canyon Wash is located in Orange County northeast of Interstate 5 and drains across the new Foothill Transportation Corridor toll road (State Route 241). In its lower reaches (downstream from the study reaches) the wash is confined within a U-shaped concrete channel as it runs adjacent to the former El Toro Marine Corps Air Station. Borrego Canyon Wash empties into Agua Chinon Wash about 1 mile upstream from its confluence with San Diego Creek. The watershed trends from northeast to southwest. A good portion of the watershed from the former Marine Corps base upstream to the toll road is mostly undeveloped. The watershed above the toll road is fairly heavily developed, except in the Whiting Ranch Park, which occupies most of the headwaters area. The two Borrego Canyon Wash study sites are separated by a significant stream channel distance and represent distinct stream channel types. Both sites are considered to be ephemeral stream channels, and both were dry in May 2004 during field data collection.

The Borrego Canyon sites, both upstream and downstream, are formed in alluvial materials consisting of sands and gravels. While both sites have wide, shallow channels, the upstream site has the widest channel of all the study sites, averaging 95 feet.

**Serrano Creek.** Serrano Creek is located in Orange County. It is similar in size, shape, and alignment to Borrego Canyon Wash and shares a common watershed boundary to along the northwestern side. However, the Serrano Creek watershed is developed to a greater extent than Borrego Canyon wash. Much of the lower portion is occupied by residential development. The middle portion contains primarily commercial type development, although some open space is present. The upper portion has significant areas of residential development, but also contains the Whiting Ranch Wilderness Park. Serrano Creek is a tributary to San Diego Creek with a confluence just east of Interstate 5. The Serrano Creek study site is upstream from Dimension Drive. Although once this site was considered to be an ephemeral stream channel, because of the degree and proximity of development, this site appears to have a small amount of base flow most of the time.

Serrano Creek has a soft sedimentary bedrock that forms the channel bed and most of the channel banks. It is the most deeply entrenched study site, and has the smallest width to depth ratio (averaging less than 4).

**Santiago Creek.** Santiago Creek is located in Orange County. It is a tributary to the Santa Ana River and drains portions of the southern flank of the Santa Ana Mountains. The watershed is mostly undeveloped except for pockets of houses along Modjeska Canyon Road between Santiago Canyon Road and the Tucker Wildlife Sanctuary. The upper part of the watershed is in the Cleveland National Forest and is undeveloped. This site is considered to be an ephemeral stream channel, and it was dry in May 2004 during field data collection. Santiago Creek serves as a control site.

Santiago Creek is formed in alluvial material that appears to have been modified somewhat by earthmoving equipment to help maintain a flood protection berm adjacent to the channel. This was probably associated with the last major flood event in 1995, and natural hydrologic forces have been at work modifying and maintaining the channel configuration since.

**Dry Canyon.** Dry Canyon is located in Ventura County on the northern side of Simi Valley, less than a mile north of State Route 118. It is about halfway between the City of Moorpark and the Los Angeles County line. The watershed trends north to south and is a tributary to Arroyo Simi. Flow from Arroyo Simi empties into Arroyo Las Posas, which is a tributary to Calleguas Creek. The watershed is undeveloped except for the Lost Canyon Golf Club. This site is considered to be an ephemeral stream channel, and it was dry in May 2004 during field data collection. Dry Canyon serves as a control site. The Dry Canyon channel is formed in alluvium, though the bed material is primarily sand and the banks are fairly cohesive. This has resulted in a width to depth ratio that is among the smallest of the study sites (averaging less than 6).

**Hicks Canyon Wash.** Hick's Canyon Wash is located in the foothills of the Santa Ana Mountains in Orange County. It is a tributary to Rattlesnake Wash, which empties into Peters Canyon Wash before it discharges into San Diego Creek. The site reach is north of Portola Parkway, south of the Foothill Transportation Corridor Toll Road, and just east of the Hicks Canyon Haul Road. Most of the watershed is undeveloped. This site is considered to be an ephemeral stream channel, and it was dry in May 2004 during field data collection. Hicks Canyon serves as a control site.

Hicks Canyon appears to be entrenched into a thick (greater than 10 to 20 feet) alluvial sequence. The channel bottom consists of sands with minor amounts of gravel. The banks are made of similar materials that are cohesive. Consequently, the channel has the smallest width to depth ratio of any of the alluvial channels (averaging just over 5).

### 3.2 Suitability of Selected Sites

One of the great difficulties in this project was locating suitable study sites, due to the specific requirements of the site selection guidelines. Thus it is reasonable to inquire about the satisfaction of selection guidelines by the final sites included in the study. A summary of how well these sites meet the selection guidelines is provided below. There is no specific order of importance of the selection guidelines, however, the first five are all equally important and critical for a successful outcome.

**Small Watershed Size.** The desired CDA size range for a selected study site was between 1 square mile and 5 square miles. As shown in Table 3-1, all of the study sites fell within this size range, except Topanga Creek and Santiago Creek, both of which are control sites. Thus, all of the watersheds that have experienced some level of development (i.e. the altered sites) are within the desired watershed size range.

**Shear Stress Dominated.** Streams that have movable beds and erodible banks under the normal range of stream flows (from frequent to infrequent) are considered to be "Shear Stress Dominated." In general this includes channels formed in alluvial materials, but not those formed in bedrock materials. The latter are generally considered to be "bedrock dominated" channels. By this definition, all of the channels included in this study would be considered as shear stress dominated, except Serrano Creek. However, the bedrock in the site reach of Serrano Creek is considered to be soft enough that normal stream flows can erode it.

On the other hand, Topanga Creek, although technically an "alluvial" channel is somewhat limited in its erodibility. The alluvial materials present are dominated by extremely large particle sizes, and are also underlain by resistant bedrock. Therefore, it is very difficult to move these alluvial materials with the frequent (smaller size) flows, and even more difficult to move or erode the bedrock even with rare flood events.

**Natural Channel.** The stream channel sites used by this study needed to be found in a more or less "natural" state, meaning that they are not controlled by engineering works. By this definition, all of the sites included in this study have natural channels with freedom to deposit or erode bed material or bank material, and alter their geometry by the action of their flows. Many of these channels have "unnatural" stretches either upstream or downstream, and sometimes both. The control sites had very limited amounts of unnatural channel reaches, while the developed watershed sites generally at least had downstream engineering works. One of the control sites, Santiago Creek, had evidence of anthropomorphic manipulation in that a berm had been constructed to limit the flooding extent on the valley bottom for very large flows. However, this berm was well away from the active channel and did not impact the channel configuration of the bankfull (Dominant Discharge) stage. Therefore, the site is considered acceptable as a natural, or self-formed stream channel reach.

**Watershed Development.** Because this study evaluates the impacts from watershed development on natural stream channels, it was equally necessary to have study sites that included watershed development, except in the control sites. The desired level of development, in terms of impervious area, was a TIMP value of between 5% and 10%. As will be discussed in Section 5, the sites with developed watersheds had TIMP values that ranged from 3.3% to 26.7% (see Table 5-1 in Section 5). In contrast, the control sites had TIMP values that remained very constant throughout the time period that was evaluated, and these ranged from 0.2% to 2.8%. Additional details about the measurement of impervious cover and its change over time in the developed watersheds is provided in Appendix A1.

**Historic Cross Sections.** Historic cross section surveys provide the means by which channel change can be measured. Therefore, the availability of such surveys for each of the study sites was imperative. The number of historic cross section locations for each site varied, as did the number of times each was surveyed previously, and the total time span covered. Most of the sites had only one previously surveyed cross section (Topanga, Hasley u/s, Hasley d/s, Plum d/s, Borrego u/s, and Borrego d/s). However, all but the Topanga cross section were surveyed more than once. The remaining sites had multiple cross section locations surveyed (Plum u/s: 2, Serrano: 3, Santiago: 4, Dry: 3, and Hick's: 2). Table 2-3 provides background on the match-up between historic sections and sections resurveyed during field data gathering for this project. Appendix Table A4-1 gives details concerning the dates of the previously surveyed cross sections.

**Stream Flow Data.** Although important, stream flow data was not imperative since engineering practice has provided the means by which flows can be estimated. Certainly actual flow measurements are superior to use than estimated values, but the stream gaging network in southern California is limited. Therefore, a single and distinct stream gage for each of the sites providing accurate and substantive coverage of the stream flow history of each stream was not expected, nor was it realized. Two channels did have stream flow records of significant length at or near the site location, Topanga Creek and Santiago Creek. Other stream gages were located in general proximity to the remaining sites (see Figures 2-2 and 2-3 for the locations). Table 2-4 identifies the stream gage records used in this project, and Appendix A2 provides the annual peak flow record available for each of these gages.

**Aerial Photos.** Available aerial photos can be used for evaluating land use changes over time, and if they are of a large enough scale, can provide information on channel plan form at specific points in time. Photos obtained for this project were limited in coverage (Table 2-2) and not detailed enough to show channel plan form at any of the study sites.

**Topographic Maps.** Us of topographic maps for evaluating channel form changes requires that they be at a very detailed scale. The guideline established for this use in the current project was for amps with a scale of least 1 inch equals 100 feet (or better) and a contour interval of 1 foot. No contour maps meeting these guidelines were identified for any of the study sites.

**Geotechnical Data.** Geotechnical data (descriptions of the soil/sediment materials) were sought to provide historical comparisons with the current data collected at each site of bed and/or bank material. Unfortunately, no geotechnical data was located for any of the study sites.

In summary, the selected study sites meet the critical guidelines established for site selection in this project very well, with one exception. Topanga Creek is limited in that there is only one historic cross section, and it was surveyed relatively coarsely compared to the other historic cross sections surveyed for the other study sites. In addition, the specific location of the historic Topanga Creek section was not reoccupied with a high level of confidence. None-the-less, the data generated for this site is valuable as it provides information for a channel type and watershed size not included in the other sites. This allows better definition of the results as it provides a broader spectrum of plotting positions in many of the deterministic relationships and channel adjustment relationships discussed in later sections of this report. The final sites selected are considered to provide a reasonably robust data set. The main limitations of these data are the relatively short period of time that is covered by the historic period and the similar channel types of all the sites except Topanga Creek and Serrano Creek. However, this is an unavoidable limitation of the study.

# 4.0 STREAM CHANNEL CLASSIFICATION SYSTEM

Different stream types respond to changes in peak flow in different ways. Therefore, it was necessary to develop a classification system to organize relationships between impervious cover and channel stability and guide management decisions for each stream type. The classification system proposed here focuses on the relevant physical attributes of the system starting with large-scale features (the watershed) and progressing toward detailed consideration of bed and bank properties for specific stream channel reaches.

The framework for the proposed classification system includes three primary factors, or levels that can be used to systematically separate sites into similar management units based on physical characteristics. Each level has a different focus with a specific set of considerations that are described in the subsections below. The levels can be summarized as follows. Details about selecting features of form and process used in classifying streams are provided in Appendix C1.

- **Level 1. Watershed Characteristics.** The first step in classification is to define the nature of the watershed. Watershed characteristics include the physical attributes of the basin including size, shape and topography that may affect runoff patterns in the stream of interest.
- **Level 2. Stream Channel Characteristics.** The next step in classifying stream reaches is to define the stream channel type. Stream channel characteristics involve the stream channel morphology, channel form (shape and slope), energy potential (flows in the stream channel), and degree of alteration
- **Level 3. Stream Channel Resistance.** The third step in classification is an assessment of the expected, or potential, responsiveness of the stream channel system to perturbations in the watershed system by such things as changing land uses. This level focuses on a characterization of the ability of the stream channel to resist erosion based on the inherent mechanical properties of the bed and banks.

## 4.1 Watershed Characteristics

The first factor for differentiating sites is the size and nature of the watershed, or catchment drainage area (CDA). Zielinski (2002) provides a useful classification of CDA size in urban streams (Table 4-1). An alternate size discriminator could be stream order, though assigning stream order is dependant on the map scale used and the mapping methodology. Because there currently is no consistent regional map that includes all ephemeral and intermittent streams, stream order is not recommended as an alternative for CDA.

The focus of the present study was on smaller drainage areas that generally are more responsive to changes in impervious surface area. Therefore, the proposed classification system focuses on small watershed management units that fall within the size range of the subwatershed- and catchment-size categories of Table 4-1.

While CDA is the most obvious differentiator among watersheds, it is by no means the only characteristic that can be used. Topographic relief, shape, and location within the study region can all affect rainfall-runoff response. However, CDA is likely to have the greatest effect on runoff, so it is the focus of Level 1 of the proposed classification system.

Watershed management units should be delineated in three size ranges, defined by their degree of sensitivity to land use change (Table 4-2). In general, priority should be given to the management of the smallest units first (2.5 square miles or less) as they provide the greatest sensitivity to change and are the most responsive to management actions. Zielinski (2002) offers several other considerations for delineating watershed management unit boundaries.

**Table 4-1. Possible Watershed Management Units**

| Watershed Management Unit | Typical Area of Feature ($mi^2$) | Relative Influence of Impervious Cover | Sample Management Measure |
|---|---|---|---|
| Catchment | 0.05 – 0.5 | Very strong | Stormwater management and site design |
| Subwatershed | 0.5 – 30 | Strong | Stream classification and management |
| Watershed | 30 – 100 | Moderate | Watershed based zoning |
| Sub-Basin | 100 – 1,000 | Weak | Basin planning |
| Basin | 1,000 – 10,000 | Very Weak | Basin planning |

From: Zielinski, 2002.

**Table 4-2. Level 1 CDA Categories**

| Category | Designation | CDA ($mi^2$) | Explanation |
|---|---|---|---|
| Very sensitive | i | ≤ 2.5 | Basins of this size show the greatest rates of change in response to urbanization. It is easier for development to impact a larger portion of the CDA. |
| Mildly sensitive | ii | ≤ 10.0 | Between 2.5 and 10.0 square miles the rates of change in stream channel morphology in response to changes in impervious area fall significantly. |
| Least sensitive | iii | ≤ 20.0 | Basins larger than 10 square miles but less than 20 square miles show some sensitivity to changes in impervious area, but less than the smaller subwatershed areas. |

- *Subwatershed size.* In addition to the guidelines in Table 4-2, start delineations downstream from tributary junctions (rather than upstream),
- *Jurisdictional boundaries.* Keep watershed management units entirely within a single jurisdiction(cities, counties, etc.) where possible,
- *Impoundments or stormwater management facilities.* Delineate from the outlet of ponds, lakes, or detention/retention basins,
- *Monitoring stations.* Include existing monitoring stations (stream gages, water quality sample points, etc.) within watershed management unit boundaries where possible,
- *Access points.* Delineate from existing roads or bridges to provide easier access for sample collection or field surveys.

## 4.2 Stream Channel Characteristics

Level 2 of the classification system focuses on the stability/state of a particular stream reach (Table 4-3). Stream channels are divided into stable or unstable based on the results of the RGA (see Section 5.7). The RGA is a semi-quantitative method for evaluating the stability of a site based on geomorphic indicators observed and recorded in the field. The RGA produces a stability index (SI) that can be used to categorize the geomorphic condition of the stream reach (SI scores range from 0 –1.0). A stability index (SI) score of 0.25 or less indicates that the stream channel is stable, while anything greater that 0.25 indicates that the stream channel is unstable. Alternatively, a qualitative assessment of geomorphic stability can be performed based on observable field evidence of channel instability, such as excessive deposition of sediment, stream channel widening, and/or stream channel scour that is noticeably divergent from upstream and downstream reaches. Unstable stream channels are already reacting to some hydrologic or sediment regime change within the watershed, and therefore have little to no tolerance for additional change to the hydrologic or sediment regime. Unstable stream channels receive no additional classification at this level and are only considered further at the final classification level (Level 3, Stream Channel Responsiveness). Stable stream channels do not show noticeable signs of either aggradation or degradation throughout the reach under consideration. Altered stream channels, i.e. those that have been modified through direct, engineered changes, such as stream channel lining, bed or bank protection, relocation or realignment, stabilization, are not considered further in this classification system, because they fall outside the scope of the present study.

Following the general assessment of stability, stream channels should be further classified according to their morphology (see Table 4-3). The data needed for this classification are the stream channel slope (as measured in the field over a distance of 10 times the stream channel width), and unit discharge (discharge divided by the width of the stream channel). The elevations used to calculate slopes should be a consistent stream channel feature such as the deepest point in the stream channel (thalweg) or the toe of a common bank for the length of the stream channel used. The distance measured for slope calculation should be the curvilinear distance along the flow-line of the stream channel, again using a common feature such as the thalweg (i.e. deepest portion of the channel) or the toe of a bank.

Because discharge data is often not readily available on any given stream, or at any specific point along a stream channel, we recommend using the USGS regional equations (Waananen and Crippen 1977) to calculate the 2-year recurrence interval storm discharge ($Q_2$), as indicated below. The 2-year equation is selected as the lowest value in recurrence interval for any of the regional equations and the closest to an assumed recurrence for the dominant discharge (1.5 to 2.0 years).

$$\mathbf{Q_2} = 0.14\ \mathbf{CDA}^{0.72}\mathbf{P}^{1.62} \qquad [4.1]$$

Where: **CDA** is catchment drainage area ($mi^2$)

**P** is average annual precipitation (in.)

The precipitation value should be selected for a weather monitoring station near the watershed being classified. Selected values of average annual precipitation for stations located in the vicinity of the sites in this investigation are given in Table 4-4. Stream channel widths should be measured in the field at the same time stream channel slopes are measured. Two to four width measurements should be made and averaged to provide the width used to define stream channel morphology with Figure 4-1. The width feature to measure is the top of the "bankfull" channel, which is defined as the top of the "active" channel, which should be discernable (the active channel) by a lack of permanent vegetation and/or the presence of obvious stream channel deposit features such as bar deposits.

**Table 4-3. Level 2 Stream Channel Morphology**

| Condition | Current State | Category | Designation | Indications |
|---|---|---|---|---|
| Altered | Altered | | X | Altered stream channels already have had permanent instream management actions applied; they are no longer considered to be natural |
| Natural | Unstable | | Un | Unstable stream channels show signs of change to the stream channel morphology such as aggradation (excessive sediment deposition), stream channel widening (one or both channel banks have fresh, cut surfaces or undermined bank materials), or channel scour (loose material on the channel bed is scarce and adjacent bank height is significantly different from stable upstream or downstream reaches. |
| | Stable | Tranquil | St-t | Slope of the stream channel appears to be very shallow; when water is flowing the velocity is relatively slow. Sediment load is very low. |
| | | Anastamosing | St-a | Anastamosing stream channels also have shallow slopes, but slightly steeper than tranquil stream channels. Sediment load is low. Stream channel pattern can be very sinuous, with multiple, inter-twining stream channel threads. |
| | | Meander, Pool-Riffle | St-m | The meandering stream channel is a single conveyance with a slightly to moderately sinuous form that has periodically spaced shallow, rapid flowing water in "riffles" interspersed with deeper "pools." Depending on sediment type and load riffles can be more transient (fine sediment) or more permanent (coarse sediment) under higher flows. Point bar deposits and cut banks alternate along opposite sides of the stream channel. |
| | | Braided, Cascade-Pool | St-b | The braided stream channel is wide, shallow, and steep with multiple, inter-twining conveyances and an abundant sediment load. Shifting channel positions are common after, or during, periods of channel flow. |
| | | Step-Pool, Canyon | St-s | Cascade-Pool channels are also steep, but have an abundance of very coarse sediment that is beyond the normal capacity of flood flows (except in very rare, high discharge rates). These materials tend to armor the channel and form very persistent, steep-flowing riffle features. |

The flow and channel data described above can be used to calculate a unit stream power (2-year peak flow divided by channel width) ($Q_2/w$). The unit stream power can be plotted against the stream channel gradient for each site (Figure 4-1), This relationship will define the expected form of the stream channel based on measurements of its energy. Deviations from the expected form indicate that the stream reach is in the process of adjusting to a new form. This is discussed in more detail in the next section.

**Table 4-4. Selected Annual Precipitation Averages**

| Station ID | Station Name | Latitude | Longitude | Elevation (feet) | Years of Record | Ave. Annual Precipitation (inches) |
|---|---|---|---|---|---|---|
| LA DPW # 6 | Topanga Patrol | 34.084167 | 118.599167 | 745 | 77 | 23.94 |
| LA DPW # 372 | San Fran. Pwr Hs | 34.533889 | 118.524167 | 1,580 | 63 | 16.22 |
| LA DPW # 801B | Magic Mountain | 34.38833 | 118.324167 | 4,720 | 37 | 17.53 |
| LA DPW # 1012B | Castaic Junction | 34.738333 | 118.611944 | 1,005 | 35 | 12.40 |
| LA DPW # 1194 | Santa Ynez Res. | 34.073056 | 118.566389 | 735 | 31 | 20.25 |
| LA DPW # 1262 | Saugus Reclam. | 34.413333 | 118.539722 | 1,150 | 19 | 13.66 |
| LA DPW # 1263 | Valencia Reclam. | 34.431944 | 118.620278 | 1,000 | 19 | 12.18 |
| OC RDMD # 121 | Santa Ana | 33.751111 | 117.869722 | 170 | 96 | 12.98 |
| OC RDMD # 165 | Costa Mesa | 33.668611 | 117.893056 | 53 | 48 | 12.14 |
| OC RDMD # 169 | Corona del Mar | 33.609722 | 117.857500 | 300 | 44 | 12.46 |
| OC RDMD # 173 | Villa Park Dam | 33.814722 | 117.766667 | 566 | 43 | 15.01 |
| OC RDMD # 176 | El Toro | 33.627500 | 117.68333 | 445 | 39 | 14.96 |
| OC RDMD # 216 | Laguna Niguel | 33.549722 | 117.70000 | 200 | 29 | 14.58 |
| CIMIS # 75 | Irvine | 33.688611 | 117.720556 | 410 | 17 | 14.24 |
| VC WPD # 154 | Simi, Co Fire Sta | 34.270000 | 118.781667 | 760 | 56 | 14.85 |
| VC WPD # 193 | Santa Susana | 34,270833 | 118.706667 | 950 | 47 | 14.62 |
| VC WPD # 196 | Tapo Canyon | 34.328333 | 118.698333 | 1,525 | 46 | 19.20 |

## 4.3 Stream Channel Resistance

Level 3 of the classification assesses the ability of the stream channel to tolerate changes in its hydrologic and/or sediment regimes. The hydrologic regime is defined by the quantity and timing of flow, while the sediment regime is defined by the texture (or size distribution) of the sediment load, the quantity of the load, and the timing of its delivery. The quickest and most direct way to evaluate a stream channel's resistance is by plotting its position on the gradient vs. stream power curve (Figure 4-1). If the plotting position of stream power vs. gradient is within the "stable energy" zone for the determined stream channel type, it can be considered as stable. Conversely, if the plotting position is close to the upper limit of the zone, it is an indication of relative instability, because it is approaching, or is within, a transition zone. For example, $\omega$ values for Site 23 (Dry Canyon) fall between the 25 and 87 Watts/ft$^2$ isoclines; therefore this site appears to be a relatively stable braided, cascade-pool system. In contrast, $\omega$ values for Site 9 (Serrano Creek) appear to be deviating from the 87 Watts/ft$^2$ isocline, indicating that the stream channel is shifting to a new morphological form.

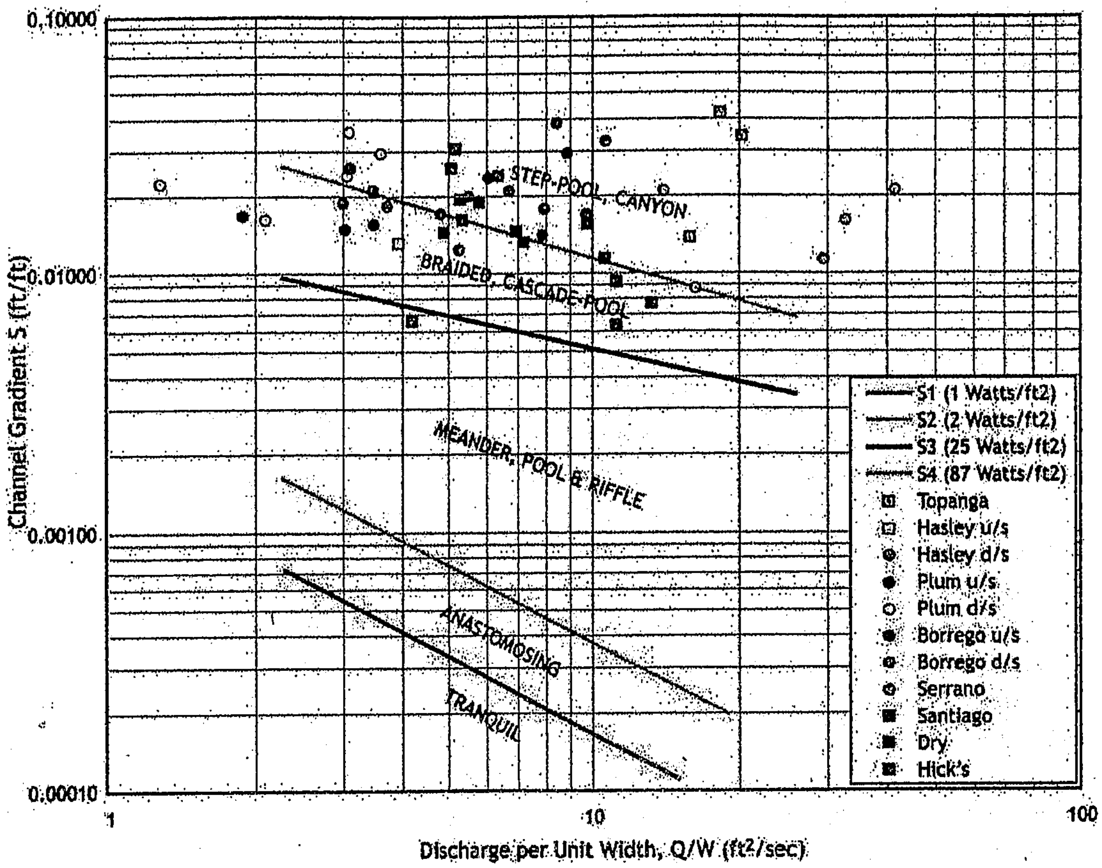



**Figure 4-1. Stream Channel Morphology**

*Stream Power (Discharge/Unit Width) versus Gradient (Longitudinal Slope) for streams within the study area. Energy ranges are defined below:*

| | Energy Range (Watts/ft²) | |
|---|---|---|
| *Classification* | *Minimum* | *Maximum* |
| *Step-pool, Canyon* | *87.0* | -- |
| *Braided, Cascade-pool* | *25.0* | *87.0* |
| *Meander-pool-riffle* | *2.0* | *25.0* |
| *Anastamosing* | *1.0* | *2.0* |
| *Non-shear stress dominated* | -- | *1.0* |

Additional qualitative classification of channel resistance can be made based on field observations of the relative erodibility of the bed and bank materials (see Table 4-5). For stable stream channels, this evaluation should confirm the plotting position on the stream channel morphology chart (Figure 4-1). In contrast, if the plotting position of a site is within the "meander, pool-riffle" stream channel morphology zone, but the field observations suggest that this site looks more like a "braided, cascade-pool" site, this is an indication that the site is not stable and is about to change stream channel morphology in response to higher energy levels. See Figure 4-2 for an example of this type of assessment.

A more rigorous assessment of the resistance provided by either the bed or the bank is possible using equations for stream power [4.2] and specific stream power [4.3]. First they must be transformed into units of applied shear stress that can be compared to a critical shear stress value for either the bed material or the bank material.

$$\Omega = \rho g Q S \qquad [4.2]$$

where:

$\Omega$ = stream power applied to channel perimeter (watts/foot)
$\rho$ = density of channel bed sediment (kilgrams/cubic foot)
$g$ = gravity (feet/second$^2$)
$Q$ = discharge (cfs) calculated for the channel configuration at which slope, width, and average depth are measured
$S$ = slope of the channel as measured in the field (feet/foot)

Dividing $\Omega$ by the stream channel width (W) produces the specific stream power.

$$\omega = \Omega/W = \rho g Q S/W \qquad [4.3]$$

where:

$\omega$ = specific stream power (watts/square foot)
$W$ = stream channel width (feet)

Specific stream power can be translated to an applied shear stress, as follows

$$\tau = \rho g d S \qquad [4.4]$$

where:

$\tau$ = average shear stress (newtons/square foot)
$d$ = average depth (feet)

Knowing that discharge is a volume per time:

$$Q = AV = WdV \qquad [4.5]$$

where:

$A$ = stream channel cross-sectional area (square feet)
$V$ = average velocity of flow (feet/second)

We can combine equations [4.2], [4.4] and [4.5] to represent stream power in terms of applied shear stress:

$$\Omega = \rho g Q S = \tau V W \qquad [4.6]$$

Finally we can express this in terms of specific stream power:

$$\omega = \tau V \qquad [4.7]$$

Sample Calculation for Channel Form (Hasley Canyon Data)

**Step 1** Estimate the drainage area of the watershed to the site and obtain a value of the average annual rainfall for the area.

CDA = 1.66 square miles (from Table 3-1)
P = 12.18 inches (from Table 4-4)

**Step 2** Calculate discharge using equation [4.1]

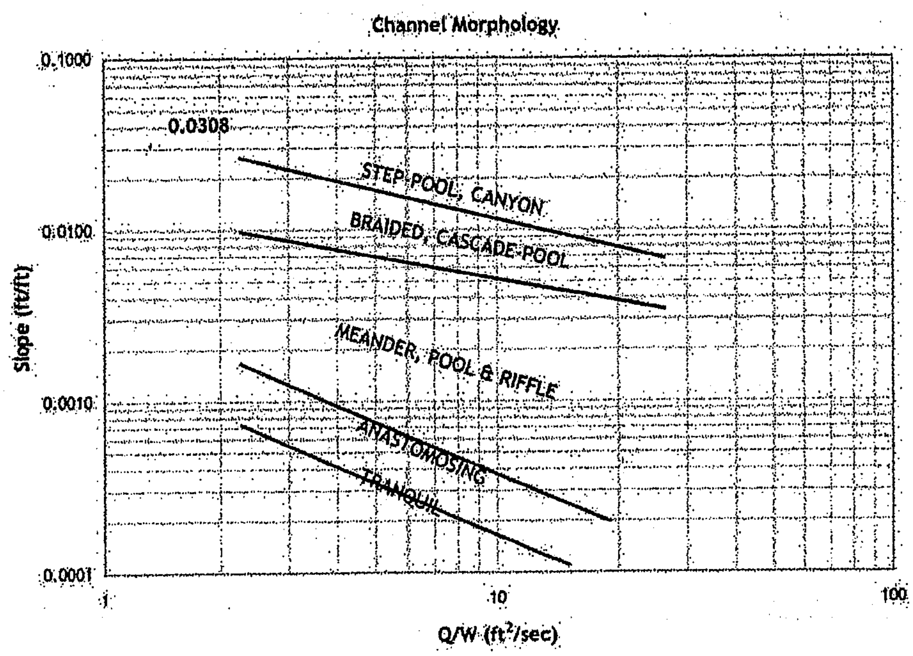
$Q_2 = 0.14 \times [(1.66)^{0.72} \times (12.18)^{1.62}]$
$= 0.14 \times [(1.44) \times (57.38)]$
$= 11.57$ cfs

**Step 3** Measure bankfull channel width and bankfull channel slope in the field. In this case we are using averages for these values measured from several points in the site reach.

$W_{bft}$ = 8.71 feet
$S_{bft}$ = 0.0308 feet/feet

**Step 4** Plot these values on the channel morphology classification chart (Figure 3-1).

$Q_2/W_{bft}$ = 1.33 square feet/second
$S_{bft}$ = 0.0308 feet/feet




**Step 5** Assess channel form as braided based on plotting position. However, field observations suggest the form is actually a step pool form.

**Figure 4-2. Example Calculation of Channel Form**

Remembering that the length term is a unit value to keep the equation dimensionally correct, it is insignificant in calculations. Therefore, specific stream power can be expressed in terms of calculated shear stress and calculated average velocity. These calculations depend on actual field measurements of the stream channel dimensions and slope, and an estimate of the flow velocity and from there an estimate can be made of the flow rate. In order to apportion the calculated specific stream power to the bed and bank, two "geometric correction" factors are introduced that resolve the specific stream power for these two different parts of the stream channel. They are used in the specific stream power equation [4.7] as follows:

$$\omega = k_b \tau V \quad [4.8]$$

$$\omega = k_s \tau V \quad [4.9]$$

where:

$k_b$ = geometric correction factor for the bed (dimensionless)
$k_s$ = geometric correction factor for the bank (dimensionless)

**Table 4-5. Level 3 Stream Channel Resistance**

| Bed Material | Bank Material: Resistant | Bank Material: Susceptible |
|---|---|---|
| Resistant | **Designation:** Bdr / Bkr<br><br>Generally true for rock channels and rock bed channels with very cohesive to indurated bank materials.<br><br>These stream channels have the most flexibility for management options as they are best at tolerating changes in hydrologic or sediment regimes | **Designation:** Bdr/ Bks<br><br>Generally true for rock bed channels with alluvial material in the bank; can also be found in alluvial channels where stream power is not sufficient to carry the current sediment load (braided channel condition). |
| Susceptible | Designation: Bds / Bkr<br><br>Unusual for arid streams, though Serrano Creek is an example; there the bed and bank material is a poorly cemented sandstone. Bank material has proven to be more resistant to erosive forces in the stream channel than has the bed material.<br><br>Channel scour occurs resulting in a deepening of the stream channel. Width to depth ratio of the stream channel should decrease. | **Designation:** Bds / Bks<br><br>Expect this to occur, if not be common, in ephemeral and intermittent stream channels. Lack of water, or even moisture, in and around the stream channel for much of the year<br><br>Stream channel scour and widening occurs at the same time. Width to depth ratio should remain relatively constant, but stream channel area (in cross-section) will likely increase. |

Using field-measured values to estimate flow (Q), the average velocity can be calculated, the length term is insignificant, and the stream power range has been read from Figure 4-2, so the applied shear stress on the bed can be calculated using equation [4.10] or the bank using equation [4.11].

$$k_b \tau = \omega / V \quad [4.10]$$

$$k_s \tau = \omega / V \quad [4.11]$$

In this case it is not necessary to know the value of the correction factors, because the whole term is used to compare to a critical shear stress value ($\tau_c$) determined for either the bed or the banks. Details of the recommended procedure for determining the critical shear stress values are given in Appendix C. A comparison is made between the estimated applied shear stress and the estimated critical shear stress representing the resistance of the bed or bank. Under stable conditions, the following expressions would be true:

$$k_b\tau \leq \tau_{cb} \quad [4.12]$$

$$k_s\tau \leq \tau_{cs} \quad [4.13]$$

where:

$\tau_{cb}$ = critical shear stress for the bed (newtons/square foot)

$\tau_{cs}$ = critical shear stress for the bank (newtons/square foot)

If either expression is untrue, then an unstable condition is present. Depending on which feature is considered stable (or unstable), or if both bed and bank are the same, the classification of stream channel resistance follows from Table 4-6. See Figure 4-3 for an example of this evaluation.

## 4.4 Classification Summary

This classification is proposed as a starting point for the development of a system that could be applied throughout the southern California region. It does not restrict the classification to ephemeral or intermittent stream channels, but would apply to perennial streams as well. Although the creation of a complete and exhaustive classification system is beyond the scope of this project, a general framework for establishing such a classification system has been presented. This classification system could be used to define characteristics of the watershed-stream channel system that are important in selecting management strategies and approaches, which are discussed in Section 7.2 (Management/Regulatory Approach). A summary of the steps of the proposed stream classification process is provided below. In addition, Table 4-6 provides a summary of the designation of each of the study sites using this classification system.

**STEP 1:** Locate the CDA within its major watershed.

**STEP 2:** Identify the CDA category (based on size)

**STEP 3:** Collect local site information and calculate $Q_2$ using regional equation [4.1] to estimate stream channel slope and specific stream power

**STEP 4:** Define stream channel form using calculations from Step 3 and plotting position from Figure 4-1

**STEP 5:** Estimate stream channel resistance using field evaluations by experienced field personnel, and/or evaluate with measured field data to compare with calculated erosive forces.

**Table 4-6. Study Site Classification**

| Study Site | Watershed Designation[1] | CDA Category[2] | Channel Form[3] | Channel Resistance[4] | Full Designation |
|---|---|---|---|---|---|
| 1. Topanga Creek | SMB | iii | St-s | Bdr-Bkr | SMB/iii/St-s/Bdr-Bkr |
| 3. Hasley Canyon | SCR | i | Un | Bds-Bks | SCR/i/Un/Bds-Bks |
| 4u. Plum Canyon | SCR | i | Un | Bds-Bks | SCR/i/Un/Bds-Bks |
| 4d. Plum Canyon | SCR | i | Un | Bds-Bks | SCR/i/Un/Bds-Bks |
| 7u. Borrego Cyn. | SDC | ii | Un | Bds-Bks | SDC/ii/Un/Bds-Bks |
| 7d. Borrego Cyn. | SDC | i | Un | Bds-Bks | SDC/i/Un/Bds-Bks |
| 9. Serrano Creek | SDC | ii | Un | Bds-Bks | SDC/ii/Un/Bds-Bks |
| 10. Santiago Ck. | SAR | iii | Un | Bds-Bks | SAR/iii/Un/Bds-Bks |
| 23. Dry Canyon | CGC | i | St-s | Bdr-Bkr | CGC/i/St-s/Bdr-Bkr |
| 27. Hicks Canyon | SDC | i | Un | Bds-Bks | SDC/i/Un/Bds-Bks |

EXPLANATIONS

1 Watersheds

CGC Calleguas Creek
SAR Santa Ana River
SCR Santa Clara River
SDC San Diego Creek
SMB Santa Monica Bay

2 CDA Size Ranges (Table 3-3)

i $CDA \leq 2.5$ mi²
ii $2.5 < CDA \leq 20$ mi²
iii 20 mi² $< CDA$

3 Channel Forms (Table 3-4)

St-b Stable, braided
St-s Stable, step-pool
Un Unstable

4 Channel Resistance (Table 3-6)

Bdr Resistant bed
Bds Susceptible bed
Bkr Resistant bank
Bks Susceptible bank

Disregarding the major watershed location, this classification system could result in one of three size categories, one of seven different channel form types, and one of four distinct channel resistance categories. Therefore, there are potentially 84 distinct classifications ($3 \times 7 \times 4 = 84$) of stream channels. The 10 stream channel sites selected for this study represent only 5 distinct channel types in this classification system. Whether or not all 84 stream types are represented in the study region remains to be evaluated.

SAMPLE CALCULATION FOR CHANNEL RESISTANCE
(Hasley Canyon Data)

**STEP 1** Establish values for variables of channel characteristics (using field measurements) and properties of water at standard conditions.

| | | | |
|---|---|---|---|
| $W_{bfl}$ | = | 10.6 ft | (from Table 5-6) |
| $S_{bfl}$ | = | 0.0264 ft/ft | (from Table 5-6) |
| $d_{bfl}$ | = | 1.7 ft | (from Table 5-6) |
| $\rho$ | = | 62 lb/ft$^3$ | (density at normal temperatures) |
| $g$ | = | 32 ft/sec$^2$ | (acceleration due to gravity) |

**STEP 2** Calculate the expected shear stress from the measured channel values using equation [4.4]:

$$\tau = \rho g d_{bfl} S_{bfl} = 62 \times 32 \times 1.7 \times 0.0264 = 89 \text{ newtons/ft}^2$$

**STEP 3** Resolve the expected shear stress from Step 2 into an applied shear force on the bed material using the geometric correction factor ($k_b$), and an applied shear force on the bank material using the geometric correction factor ($k_s$). The geometric correction factor for the bed shear stress (Lane 1955) is based on the width to depth ratio of the measured channel values established in Step 1 (10.6/1.7 = 6.2). The correction factor for the bank shear stress is also based on channel geometry (Lane 1955).

$k_b\tau$ = 0.95 x 89 = 84.6 newtons/ft$^2$ (Bed material)

$k_s\tau$ = 0.75 x 89 = 66.8 newtons/ft$^2$ (Bank material)

**STEP 4** Compare the calculated shear forces on both the bed and bank to resistance values derived with the sediment characteristics measured in the field.

84.6 newtons/ft$^2$ ≥ 57.2 newtons/ft$^2$ (Bed material)

66.8 newtons/ft$^2$ ≥ 14.8 newtons/ft$^2$ (Bank material)

**STEP 5** Assess channel resistance as Bds-Bks, or a susceptible bed and susceptible banks.

**Figure 4-3. Example Calculation of Channel Resistance**

# 5. SUMMARY OF FIELD DATA

For each of the 10 study sites, the following data was collected for both historic and current conditions: 1) characteristics of the catchment draining to the site; 2) rainfall and streamflow; and 3) physical condition of the stream channel.

Land use records and aerial photographs were used to estimate the total impervious surface area (TIMP) values in the study watersheds. Precipitation records were evaluated to gain an understanding of when the wet and dry periods occurred in the regions where the study watersheds are located, and whether or not the rainfall amounts were representative of normal conditions during both the period of land use change and the period of stream channel morphology change. The stream flow records provided data for statistical analyses of peak flow frequency for the different drainage areas and serve as a second piece of evidence to determine the representativeness of the climatic conditions during the period of urbanization. Data on bed and bank material were used to evaluate susceptibility to erosion (critical shear stress) and to help define roughness for hydraulic calculations. The results of these analyses are summarized in the sections below.

## 5.1 Impervious Surface Area (TIMP)

Data on land uses were either available in ArcGIS format (SCAG data) or were delineated on aerial photographs and imported into AcrGIS. The surface area covered by each land use type was calculated for the watershed (drainage area) of each study site. Each land use type was then assigned a specific percent impervious cover value. Total and percent impervious surface area for each watershed was then calculated based on the extent of land use types within the watershed (Table 5-1). A detailed discussion of the process, the percent impervious cover values used for each land use, and the tabulation of land uses and impervious areas by watershed is provided in Appendix A1.

A word of caution is necessary concerning the use of TIMP to represent the degree of development in a watershed and provide a quantitative value against which to relate observed channel changes. Better relationships would likely result from the use of a different representation of impervious area that accounts for the location of impervious surfaces relative to the stream channel and the connection between impervious surfaces and conveyance routes for surface runoff. Such a measurement is often called CIMP (Connected Impervious Cover) or FRIMP (the FRaction of IMPervious surface that is directly connected to another impervious surface and eventually a storm sewer or to the stream channel). However, FRIMP was not used in this study, for two reasons.

1. It is very difficult to calculate FRIMP because it requires field verification of impervious area connections based on air photo or map interpretation. Not only is it difficult and time-consuming to verify for current conditions, it is nearly impossible to verify estimates for historic conditions. Also, the cost for this level of effort is not reasonable for a regional study of this nature.

2. The bulk of the published literature on the effects of urbanization uses TIMP values, so comparisons of values for southern California would be more appropriate using TIMP values. Nevertheless, it would be useful to revisit the FRIMP values for the study watersheds and compare them to the calculated TIMP values; however, this is beyond the scope of the present study.

## Table 5-1. Impervious Area Estimates from Land Use Data

| SITE NO. | SITE NAME | PERCENT IMPERVIOUS (TIMP) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1949[1] | 1952[1] | 1967[1] | 1968[1] | 1972[1] | 1978[1] | 1982[1] | 1983[1] | 1990[3] | 1993[3] | 1997[1] | 2001[3] | 2002[2] | 2003[2] | 2004[2] |
| 1 | Topanga Creek | | | | | | | | – | 2.48% | 2.62% | | 2.82% | | | |
| 3u | Hasley Canyon (upstream) | | | | | | | | | 1.19% | 1.26% | | 1.34% | 1.34% | 1.34% | |
| 3d | Hasley Canyon (downstream) | | | | | | | | | 1.19% | 1.26% | | 1.34% | 1.34% | 3.27% | |
| 4u | Plum Canyon (upstream) | | | | | | | | | 0.15% | 0.15% | | 0.16% | | 1.73% | 16.96% |
| 4d | Plum Canyon (downstream) | | | | | | | | | 0.20% | 0.20% | | 1.64% | | 1.62% | 17.52% |
| 7u | Borrego Canyon (upstream) | | 1.00% | 1.05% | | 1.03% | | | 1.04% | 1.46% | 5.80% | 13.19% | 22.00% | | | |
| 7d | Borrego Canyon (downstream) | | 1.23% | 1.06% | | 1.06% | | | 1.08% | 1.87% | 5.08% | 11.47% | 21.00% | | | |
| 9 | Serrano Creek | 1.08% | | | 1.14% | | 1.11% | 3.74% | | 5.98% | 11.18% | 21.75% | 26.66% | | | |
| 10 | Santiago Creek | | | | | | | | | 0.23% | 0.23% | | 0.24% | | | |
| 23 | Dry Canyon | | | | | | | | | 0.06% | 0.06% | | 0.70% | | | |
| 27 | Hicks Canyon | | | | | | | | | 0.10% | 0.10% | | 1.24% | | | |

(1) Aerial Photo Interpretation
(2) DigitalGlobe® Satellite Imagery
(3) SCAG Land Use Maps

## 5.2 Precipitation

Rainfall records were obtained from various sources adjacent to each of the study areas (see Table 2-3). Rainfall data for each of the weather stations listed in Table 2-3, and plots of rainfall amounts over time are provided in Appendix A2. Precipitation data were used to help assess the relative importance of climatic factors on the observed changes in stream channel morphology for the period of land use change covered by this study. Comparisons were made between the rainfall during the post-urbanization period (i.e. the period of interest for this study) and the average annual precipitation to assess the representativeness of the time period being evaluated.(see Tables 5-2, 5-3, and 5-4). Because the empirical investigation methods employed in this study related changes in stream channel form to changes in runoff potential, no direct use of rainfall events, amounts, or intensities was made. The empirical methods attempt to look at cumulative effects rather than specific, event-related results.

Development in the Hasley Canyon and Plum Canyon watersheds has only recently begun; therefore, there is only a short period of record available since urbanization. According to the changes in impervious surface area (see Table 5-1) the limited development in Hasley Canyon began in approximately 2002, while the more extensive development in Plum Canyon began initially in 2002 and continued through 2003. Therefore, the average annual rainfall for the period from 2001 through 2003 was calculated and compared to the average for the period of record for four of the stations near these two watersheds (Table 5-2). For these watersheds, it appears that the rainfall was less than normal during the period of urbanization. Thus, climatic factors probably did not contribute to the impacts on these stream channels.More time has passed since the development in the Borrego Canyon and Serrano Creek watersheds occurred. Using the values of TIMP in Table 5-2 as a guide, the start of development for Serrano Creek was estimated to be around 1980, while in Borrego Canyon it was estimated to be around 1991. Therefore, there are enough records available to consider 3-year, 5-year and 10-year averages for annual precipitation after the start of urbanization (Tables 5-3 and 5-4). Results of these comparisons are much different than for the Los Angeles County streams, and suggest that above-average rainfalls could have played a role in the observed stream channel morphology changes in the Orange County sites. Further discussion concerning the implications of above average rainfall amounts on study results is included in Section 6.2 (Evaluating Changes in Stream Channel Condition).

**Table 5-2. Hasley and Plum Canyons Rainfall Comparisons**
*Comparison of the average precipitation for the period of urbanization to the period of record for the station.*

| | Station 372(1) | Station 801B(1) | Station 1262 | Station 1263 |
|---|---|---|---|---|
| Ave. Ann. Precip. (inches) | 16.22 | 17.53 | 13.66 | 12.18 |
| Length of Record | 63 | 37 | 19 | 19 |
| 3-Year Period | 2001-2003 | 2001-2003 | 2001-2003 | 2001-2003 |
| 3-Year Average (inches) | 11.64 | 14.88 | 13.66 | 5.86 |

(1) Only 2 years of record were available for the 2001-2003 period.

## 5.3 Stream Flow

Stream gage data for peak flows at recording stations at or near study sites were obtained from the USGS web site [http://waterdata.usgs.gov/ca/nwis/nwis] or from Los Angeles County. The data for each gaging station were prepared for plotting flow frequency curves using the Weibull formula (Haan 1977). Values were taken from these curves to prepare regional peak flow curves (CDA vs. peak discharge) for specific, low value recurrence interval events (1.2-year, 2-year, 5 year, and 10-year). Data and curves are provided in Appendix A3.

**Table 5-3. Borrego Canyon Wash Rainfall Comparisons**

*Comparison of the average precipitation for the period of urbanization to the period of record for the station.*

| | Station 121 | Station 165 | Station 169 | Station 173 | Station 167 | Station 216 |
|---|---|---|---|---|---|---|
| Ave. Ann. Precip. (inches) | 12.98 | 12.14 | 12.46 | 15.01 | 14.96 | 14.58 |
| Length of Record | 96 | 48 | 44 | 43 | 39 | 29 |
| 3-Year Period | 1991-1993 | 1991-1993 | 1991-1993 | 1991-1993 | 1991-1993 | 1991-1993 |
| 3-Year Average (inches) | 17.25 | 15.03 | 15.27 | 20.06 | 18.97 | 16.00 |
| 5-Year Period | 1991-1995 | 1991-1995 | 1991-1995 | 1991-1995 | 1991-1995 | 1991-1995 |
| 5-Year Average (inches) | 17.57 | 15.00 | 15.78 | 19.79 | 18.89 | 17.31 |
| 10-Year Period | 1991-2000 | 1991-2000 | 1991-2000 | 1991-2000 | 1991-2000 | 1991-2000 |
| 10-Year Average (inches) | 16.24 | 14.36 | 15.03 | 18.11 | 17.84 | 17.13 |

Peak flow data were also reviewed as a second approach to consider the impact of climatic factors on the change in stream channel morphology for Borrego Canyon and Serrano Creek. The Santiago Creek gage at Modjeska has a continuous record from 1962 through the present. The entire record of annual peak flows for this gage is presented in Table 5-5. The return periods of the annual peaks from 1980 through 1989 (urbanization period for Serrano Creek) show two flows above an 8-year return period. These flows ranked as the third and fifth largest flows of the 42-year record at this gage. The return periods of the annual peaks from 1991 through 2000 (urbanization period for Borrego Canyon) show two flows above a 10-year return period (ranked as the second and fourth largest flows on record). This concentration of higher than normal flows during these two periods is consistent with the conclusion that climate could have contributed to the morphological changes in the Borrego Canyon and Serrano Creek stream channels.

## 5.4 Stream Channel Characteristics

Field data gathered in May 2004 consisted of a series of cross sections and a single, longitudinal profile for the entire reach at each site. Measurements of stream channel width, cross-sectional area, average depth, and longitudinal gradient (channel slope) were made for each surveyed cross section (Table 5-6). The common feature used to standardize the measurements among the sites was the bankfull stage (i.e., the elevation/depth of flow that fills the active channel), also referred to in this study as the Dominant Discharge (see Appendix C2 for a discussion of the logic for this determination). In addition, sediments in the stream channel bed and banks were characterized. Hydraulic calculations from the data in Table 5-6 provide an estimate of discharge at the bankfull stage ($Q_{bfl}$).

**Table 5-4. Serrano Creek Rainfall Comparisons**

*Comparison of the average precipitation for the period of urbanization to the period of record for the station.*

| | Station 121 | Station 165 | Station 169 | Station 173 | Station 167 | Station 216 |
|---|---|---|---|---|---|---|
| Ave. Ann. Precip. (inches) | 12.98 | 12.14 | 12.46 | 15.01 | 14.96 | 14.58 |
| Length of Record | 96 | 48 | 44 | 43 | 39 | 29 |
| 3-Year Period | 1980-1982 | 1980-1982 | 1980-1982 | 1980-1982 | 1980-1982 | 1980-1982 |
| 3-Year Average (inches) | 16.12 | 16.30 | 16.56 | 17.79 | 15.85 | 14.45 |
| 5-Year Period | 1980-1984 | 1980-1984 | 1980-1984 | 1980-1984 | 1980-1984 | 1980-1984 |
| 5-Year Average (inches) | 15.73 | 15.38 | 15.93 | 18.16 | 17.11 | 16.15 |
| 10-Year Period | 1980-1989 | 1980-1989 | 1980-1989 | 1980-1989 | 1980-1989 | 1980-1989 |
| 10-Year Average (inches) | 16.34 | 15.90 | 16.00 | 18.68 | 17.56 | 16.17 |

Nine of the eleven sites are channels formed in relatively erosive alluvial material. The remaining two sites are bedrock controlled (i.e. outcropping bedrock in the channel and banks within, or very near to, the study reach). Although not caused by geomorphic setting, the most obvious difference in these two sites from other sites is that Topanga Creek (the largest watershed) and Serrano Creek (the most developed watershed) are the only two non-ephemeral stream channels in the study. Both channels had flowing water at the time of the survey in May 2004. However, it was not documented whether flow persisted all year (i.e. whether either stream is perennial). Despite that fact that Topanga and Serrano creeks were both bedrock controlled, differences in the composition of the bedrock influenced their relative resistivity. The Topanga Creek site consists of resistant bedrock that provides the source of coarse sediment in the channel (cobble to boulder size). In contrast, the bedrock in Serrano Creek is a poorly-consolidated sandstone that has proven to have little resistance to erosion.

Differences in channel type help explain some of the variability in channel metrics between the sites. Nevertheless it is useful to consider this data set as a whole and make some general statements about the values obtained for the existing conditions at these sites. Judging by the values in Table 5-6, the calculated discharge rates for the bankfull stage show the greatest consistency among the sites. The standard deviation for the Dominant Discharge ($Q_{bfl}$) calculated for each site show the lowest values and smallest range of values of any parameter in the table. Figure 5-1 shows the relation between CDA and the Dominant Discharge. The developed sites show higher runoff rates for similar watershed areas. On the other hand, the measured widths and slopes have the highest values and largest range of values. This is logical in that discharge should be the most dependent on watershed size, and therefore vary the least in a short channel reach. The fact that this calculated value is consistent for all of the sites demonstrates that the bankfull stage is a reliable feature to identify in the field and use for comparison purposes. It is also important to point out that the downstream sites at Plum Canyon and Borrego Canyon Wash have smaller values for the Dominant Discharge than the upstream sites. Therefore, it is apparent that in each of these reaches there is loss of flow between the upstream and downstream sites. This can be explained as a loss to infiltration into the porous materials in the channel bottom.

**Table 5-5. Stream Gage Record for Santiago Creek at Modjeska**

*Annual peak flows for the period of record (water years 1962 – 2003)*

| Rank | Peak Q (cfs) | Peak Date | Return Period (years) | Rank | Peak Q (cfs) | Peak Date | Return Period (years) |
|---|---|---|---|---|---|---|---|
| 11 | 825.00 | 16-Mar-03 | 3.91 | 20 | 386.00 | 20-Jan-82 | 2.15 |
| 42 | 3.40 | 21-Dec-01 | 1.02 | 17 | 483.00 | 29-Jan-81 | 2.53 |
| 34 | 75.00 | 25-Feb-01 | 1.26 | 5 | 1,810.00 | 18-Feb-80 | 8.60 |
| 31 | 97.00 | 21-Feb-00 | 1.39 | 14 | 555.00 | 05-Jan-79 | 3.07 |
| 41 | 5.60 | 26-Jan-99 | 1.05 | 6 | 1,550.00 | 09-Feb-78 | 7.17 |
| 2 | 6,200.00 | 23-Feb-98 | 21.50 | 39 | 16.00 | 07-Jan-77 | 1.10 |
| 24 | 257.00 | 26-Jan-97 | 1.79 | 18 | 440.00 | 01-Mar-76 | 2.39 |
| 33 | 77.00 | 21-Feb-96 | 1.30 | 28 | 185.00 | 08-Mar-75 | 1.54 |
| 4 | 2,400.00 | 05-Mar-95 | 10.75 | 13 | 575.00 | 08-Jan-74 | 3.31 |
| 36 | 36.00 | 20-Feb-94 | 1.19 | 15 | 516.00 | 11-Feb-73 | 2.87 |
| 10 | 1,370.00 | 17-Jan-93 | 4.30 | 25 | 241.00 | 25-Dec-71 | 1.72 |
| 12 | 807.00 | 12-Feb-92 | 3.58 | 35 | 56.00 | 21-Dec-70 | 1.23 |
| 23 | 274.00 | 01-Mar-91 | 1.87 | 32 | 90.00 | 02-Mar-70 | 1.34 |
| 22 | 287.00 | 17-Feb-90 | 1.95 | 1 | 6,520.00 | 25-Feb-69 | 43.00 |
| 30 | 167.00 | 25-Dec-88 | 1.43 | 26 | 211.00 | 08-Mar-68 | 1.65 |
| 27 | 203.00 | 17-Jan-88 | 1.59 | 8 | 1,420.00 | 06-Dec-66 | 5.38 |
| 40 | 13.00 | 05-Jan-87 | 1.08 | 7 | 1,500.00 | 22-Nov-65 | 6.14 |
| 19 | 396.00 | 29-Nov-85 | 2.26 | 29 | 175.00 | 09-Apr-65 | 1.48 |
| 9 | 1,400.00 | 19-Dec-84 | 4.78 | 38 | 17.00 | 02-Apr-64 | 1.13 |
| 16 | 490.00 | 24-Nov-83 | 2.69 | 37 | 30.00 | 10-Feb-63 | 1.16 |
| 3 | 3,400.00 | 02-Mar-83 | 14.33 | 21 | 302.00 | 11-Feb-62 | 2.05 |

Given that the variability of channel depth and cross-sectional area are also relatively small, the high variability in the width and slope are quite logical. Since the flow in these sites is conservative (as the data in Table 5-6 suggest) flow is not changing much over time, nor is the depth of flow or channel area. Therefore, adjustment to changes in stream power to maintain channel competency (i.e. its ability to transport sediment load) is accomplished primarily through changes in width and slope of the channels. This is easily accomplished in alluvial channels with the abundance of loose sediment material available to move and be reshaped.

### 5.5 Dominant Discharge

The concept of using a single, discrete flow to represent the actions of a range of flows that a channel experiences, is very useful. This is the basis for the use of the term *Dominant Discharge*. The actual value of the Dominant Discharge has been defined in various ways, (a) related to channel form (as in meander wavelength), (b) the flow that does the most work, statistically, in carrying sediment, or (c) the flow which fills the channel to capacity (i.e. the "bankfull stage"). Knighton (1984) asserts that there is enough evidence from previous studies to make a compelling case for a convergence of these methods of defining Dominant Discharge.

**Table 5-6. Stream Channel Site Data**
*Average values for measurements and standard deviations taken in May 2004. Actual measurements by cross section are presented in Appendix B1.*

| Site No. | Name | Value | $Q_{bfl}$ (cfs) | $A_{bfl}$ (ft$^2$) | $W_{bfl}$ (ft) | $d_{bfl}$ (ft) | $S_{bfl}$ (ft/ft) |
|---|---|---|---|---|---|---|---|
| 1 | Topanga | Average | 1,427.4 | 191.1 | 75.7 | 6.0 | 0.0298 |
| | | Stnd. Dev. | 3.4% | 18.0% | 9.7% | 3.6% | 48.3% |
| 3 | Hasley | Average | 71.0 | 11.4 | 10.6 | 1.7 | 0.0264 |
| | | Stnd. Dev. | 7.8% | 21.5% | 38.1% | 12.8% | 43.4% |
| 4u | Plum Upstream | Average | 267.7 | 49.1 | 53.7 | 2.2 | 0.0216 |
| | | Stnd. Dev. | 11.2% | 20.0% | 49.2% | 23.1% | 15.6% |
| 4d | Plum Downstream | Average | 127.8 | 32.6 | 54.8 | 1.1 | 0.0257 |
| | | Stnd. Dev. | 7.5% | 19.5% | 42.7% | 22.7% | 28.1% |
| 7u | Borrego Upstream | Average | 343.5 | 79.0 | 95.1 | 1.7 | 0.0183 |
| | | Stnd. Dev. | 4.2% | 32.1% | 59.9% | 6.5% | 34.6% |
| 7d | Borrego Downstream | Average | 248.1 | 54.2 | 54.7 | 1.9 | 0.0170 |
| | | Stnd. Dev. | 11.5% | 16.7% | 34.0% | 18.1% | 15.5% |
| 9 | Serrano | Average | 346.1 | 43.2 | 17.0 | 5.2 | 0.0157 |
| | | Stnd. Dev. | 3.3% | 16.9% | 34.7% | 22.1% | 35.4% |
| 10 | Santiago | Average | 752.1 | 136.3 | 69.9 | 3.9 | 0.0101 |
| | | Stnd. Dev. | 8.9% | 16.4% | 7.7% | 14.6% | 35.9% |
| 23 | Dry | Average | 55.5 | 11.2 | 9.6 | 1.7 | 0.0163 |
| | | Stnd. Dev. | 7.6% | 9.6% | 13.2% | 10.6% | 17.8% |
| 27 | Hicks | Average | 48.3 | 9.1 | 8.7 | 1.7 | 0.0208 |
| | | Stnd. Dev. | 11.9% | 18.0% | 13.0% | 14.1% | 45.9% |

The single flow identified as Dominant Discharge is often thought of as a "channel forming" flow that is responsible for the present shape of a natural stream channel. However, the Dominant Discharge is actually just concept, and represents the variability in flows of each watershed. Nevertheless, because of the demonstrated tendency of the Dominant Discharge to be coincident with the current channel form, the bankfull stage can be used to estimate Dominant Discharge. This application is adopted for this study, and the Dominant Discharge is used as a surrogate for the range of geomorphic activities in the channel. Consequently, it provides an effective comparative value among channels.

The obvious concerns with using this feature are how well adjusted it is to the range of flows that are currently representative of watershed activity, and how accurately it can be measured for any given stream channel segment. Both of these sources of error can be significant, but this is an accepted level of uncertainty in geomorphic research when drawing deterministic conclusions about stream channel activity in natural systems. Perhaps the uncertainty is even greater than normal when dealing with bankfull features in semi-arid systems because the channel form can be unduly impacted by the most recent major storm to reach the watershed. Graf (1988) provides a strong argument for the importance of recent flows in dryland watersheds. However, even with the complexities of the relationship between channel form and the range of flows within a watershed (and their timing), this use of the Dominant Discharge concept provided the best opportunity to draw meaningful conclusions about channel behavior in these semi-arid locations.

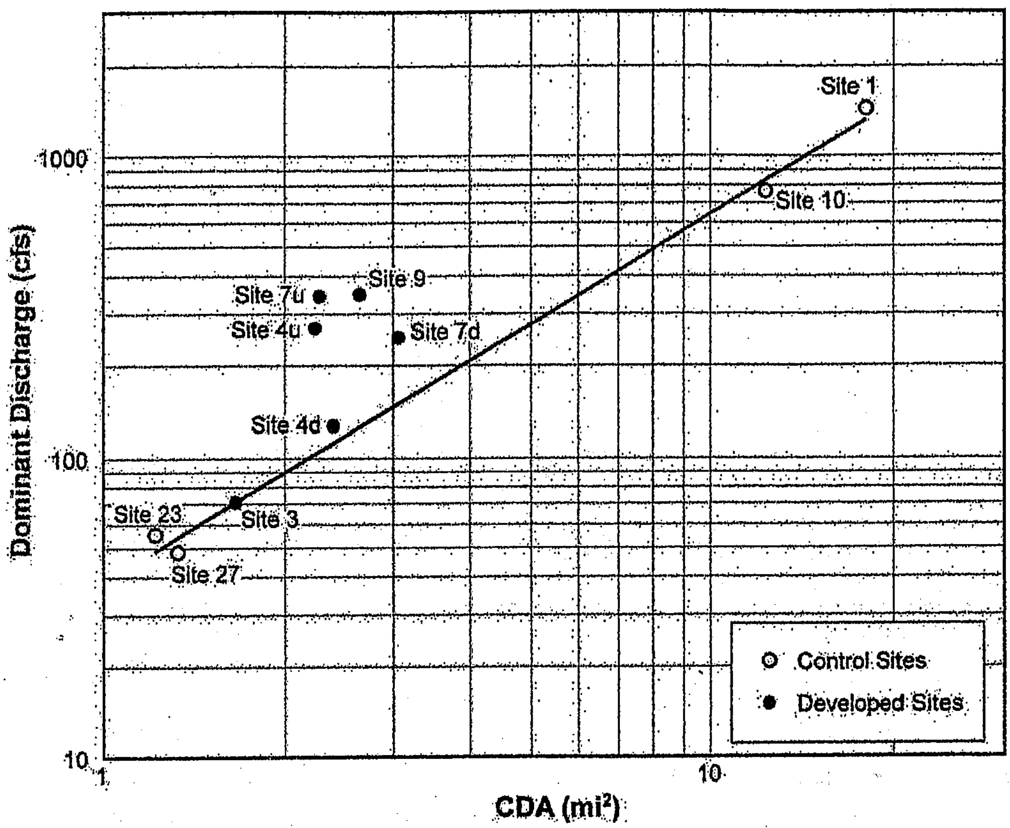



**Figure 5-1. Discharge and Drainage Area**

*The reference line is a best fit for the control sites. Most of the sites with developed watersheds are well above the line, demonstrating greater runoff per unit area than the control sites.*

Concerning the specific data for the study sites, the Dominant Discharge calculated for each cross section at every site is based on bio-geomorphic indicators (see Appendix C2). Of interest to this study, as well as urban stormwater managers, is the relative frequency of these discharges. It is well established in the literature that urbanizing watersheds (in the absence of stormwater management measures) have an increase in runoff associated with a storm of a similar frequency. Therefore the return period of the discharge associated with the bankfull stage, the Dominant Discharge, is significant for comparing these sites. Table 5-7 provides two estimates of the value of the return period for the calculated Dominant Discharges for a specific cross section at each of the sites.

Recurrence intervals are estimated with two distinct methods as a means of comparing and validating results. The first method employs the regional equations developed by the U.S. Geological Survey (Waananen and Crippen 1977) to estimate peak discharges for ungaged basins. These equations provide estimates of peak flow for specific recurrence intervals based on watershed size (CDA) and average annual rainfall amounts. Graphs were prepared for each site, plotting recurrence interval vs. discharge, using these equations and specific CDA values and rainfall amounts. The Dominant Discharge calculated for a cross section can then be plotted on the graph to estimated recurrence interval. A more detailed description of this process and the results are provided in Appendix C2.

**Table 5-7. Recurrence Interval Estimates**
*Values estimated for current conditions at specified cross sections*

| Study Site | Section | Date of Survey | Dominant Discharge $Q_{bn}$ (cfs) | Recurrence Interval USGS Estimate (yrs) | Prorate to Gage (yrs) |
|---|---|---|---|---|---|
| 1 Topanga Creek | TOP-02 | 4-May-04 | 1,381.4 | n/a | 2.4 |
| 3u Hasley Canyon | HAS-04 | 9-May-04 | 64.8 | 6.2 | 2.1 |
| 3d Hasley Canyon | HAS-02 | 9-May-04 | 77.5 | 6.6 | 2.1 |
| 4u Plum Canyon | PLU(u/s)-05 | 11-May-04 | 308.2 | 3.9 | 5.7 |
| 4d Plum Canyon | PLU(d/s)-02 | 10-May-04 | 127.8 | 7.3 | 2.5 |
| 7u Borrego Canyon | BOR(u/s)-03 | 6-May-04 | 327.7 | 10.5 | 6.7 |
| 7d Borrego Canyon | BOR(d/s)-03 | 7-May-04 | 292.2 | 6.6 | 3.9 |
| 9 Serrano Creek | SER-03 | 7-May-04 | 353.6 | 2.8 | 5.6 |
| 10 Santiago Creek | SAN-01 | 13-May-04 | 754.4 | 1.5 | 4.1 |
| 23 Dry Canyon | All stations | 11-May-04 | 55.6 | 6.4 | 2.3 |
| 27 Hick's Canyon | HIC-04 | 8-May-04 | 54.8 | 6.0 | 2.2 |

The second method uses gage records to develop flow frequency curves from which return periods can be read for a corresponding discharge. However, the flow frequency curve is specific for the CDA to the gage. Therefore, the Dominant Discharge calculated for a specific cross section at a study site must be prorated by CDA size to obtain the corresponding flow rate at the gage before its return period can be read from the flow frequency curve.

## 5.6 Bed and Bank Material

A summary of the particle-size distributions of the channel bed sediment evaluated during field assessment for the current study is given in Table 5-8. The material characterized represents the coarse fraction of bed sediment that is actually or potentially the sediments that result in natural channel armoring. The $\phi_{16}$, $\phi_{50}$, $\phi_{75}$, and $\phi_{84}$, values represent the sediment particle size diameter for which 16%, 50%, 75%, and 84% of the cumulative size distribution is smaller. These material size values have been used in the evaluation of channel bed resistance to erosion. In addition to the coarse sediment fraction, the finer sediments were characterized with sieve analyses in the field. The fact that all of these sites had bed sediment $\phi_{50}$ sizes ranging from sand size (0.01 in. to 0.08 in.) to boulder gravel (greater than 10 in.) indicates that they are poorly to very poorly sorted sediments. The $\phi_{50}$ size values in Table 5-8 classify most of the "armor fraction" of these sediments in the cobble gravel size range (2.5 in. to 10 in., Compton 1962). The only real distinction among these sites based on sediment size is the order of magnitude difference of the Topanga sediment from the other sites.

A Torvane® shear meter was used to measure the cohesion of the bank materials. The size distributions of bank materials as a description of cohesion (using units of applied shear force) are ultimately used in evaluating the susceptibility of the bed and bank materials to erosion based on the estimated applied shear forces of the Dominant Discharge. Results of the analysis of sediment data, including the size-fraction distribution, are provided in Appendix B2.

### Table 5-8. Summary of Particle Size Data

*Values presented in this table are from pebble counts, using the Wolman (1954) method, of the coarsest materials in the channel bed at each cross section.*

| Watershed | Cross-Section ID | Equivalent Diameter For Selected Particle Size Fractions | | | |
|---|---|---|---|---|---|
| | | $\phi_{16}$ (in) | $\phi_{50}$ (in) | $\phi_{75}$ (in) | $\phi_{84}$ (in) |
| Topanga Canyon | TOP-01 | | 29.95 | | 44.98 |
| | TOP-02 | | 35.65 | | 44.96 |
| | TOP-03 | | 17.49 | | 22.13 |
| Hasley Canyon Upstream | HAS-04 | 2.05 | 3.46 | 4.72 | 5.00 |
| Hasley Canyon Downstream | HAS-01 | 2.95 | 5.04 | 5.71 | 5.94 |
| | HAS-02 | 2.05 | 2.83 | 3.19 | 3.27 |
| | HAS-03 | 2.13 | 2.91 | 3.15 | 3.23 |
| Plum Canyon Upstream | PLU-01u/s | 2.01 | 3.11 | 3.62 | 3.78 |
| | PLU-02u/s | 3.43 | 5.87 | 7.60 | 8.15 |
| | PLU-03u/s | 1.97 | 3.07 | 3.66 | 4.02 |
| | PLU-04u/s | 2.99 | 5.39 | 7.20 | 7.72 |
| | PLU-05u/s | 2.60 | 3.94 | 4.76 | 4.96 |
| Plum Canyon Downstream | PLU-01d/s | 4.09 | 8.15 | 9.13 | 9.21 |
| | PLU-02d/s | 2.40 | 3.15 | 3.35 | 3.43 |
| | PLU-03d/s | 2.17 | 3.35 | 3.82 | 4.06 |
| | PLU-04d/s | 1.93 | 3.62 | 5.67 | 5.79 |
| Borrego Canyon Wash Upstream | BOR-01u/s | 3.74 | 6.93 | 8.43 | 8.98 |
| | BOR -02u/s | 3.15 | 4.69 | 5.55 | 5.83 |
| | BOR -03u/s | 3.19 | 3.82 | 4.37 | 4.49 |
| | BOR -04u/s | 3.74 | 5.20 | 5.79 | 6.02 |
| | BOR -05u/s | 3.19 | 5.20 | 6.57 | 7.52 |
| Borrego Canyon Wash Downstream | BOR-01d/s | 2.56 | 3.43 | 3.98 | 4.25 |
| | BOR -02d/s | 4.80 | 8.11 | 9.53 | 9.92 |
| | BOR -03d/s | 2.60 | 4.41 | 5.35 | 5.63 |
| | BOR -04d/s | 2.32 | 4.13 | 5.59 | 5.91 |
| | BOR -05d/s | 3.94 | 7.09 | 7.48 | 7.56 |
| Serrano Creek | SER-01 | 3.19 | 4.21 | 5.16 | 5.35 |
| | SER-02 | 3.94 | 6.89 | 7.52 | 7.60 |
| | SER-03 | 2.64 | 4.17 | 5.67 | 5.91 |
| Santiago Canyon | SAN-01 | 1.81 | 3.35 | 4.17 | 4.41 |
| | SAN-02 | 2.28 | 5.83 | 6.81 | 7.05 |
| | SAN-03 | 7.13 | 8.90 | 9.37 | 9.84 |
| | SAN-04 | 2.68 | 5.08 | 5.35 | 5.43 |
| | SAN-05 | 2.36 | 3.74 | 4.72 | 5.24 |
| Dry Creek | DRY-01 | 2.76 | 4.76 | 6.38 | 6.50 |
| | DRY-02 | 3.39 | 5.59 | 6.06 | 6.22 |
| | DRY-03 | 1.93 | 3.11 | 3.43 | 3.58 |
| | DRY-04 | 2.44 | 3.39 | 3.98 | 4.45 |
| Hick's Canyon Wash | HIC-01 | 4.06 | 7.64 | 8.98 | 9.41 |
| | HIC-02 | 2.48 | 3.58 | 5.12 | 5.43 |
| | HIC-03 | 0.87 | 1.22 | 1.30 | 1.46 |
| | HIC-04 | 0.87 | 1.10 | 1.26 | 1.34 |
| | HIC-05 | 1.97 | 3.70 | 4.13 | 4.13 |

## 5.7 Rapid Geomorphic Assessment

Channel stability at each site was evaluated using a Rapid Geomorphic Assessment (RGA). The RGA is a semi-quantitative method for evaluating the stability of a site based on geomorphic indicators observed and recorded in the field. The RGA produces a stability index (SI) that can be used to categorize the geomorphic condition of the stream reach. The calculated stability index values suggest that all of the study sites are either already unstable or are in transition to being unstable (Table 5-9). The two control sites, Hicks and Dry canyons, had the lowest SI scores while more developed watersheds, such as Plum and Serrano canyons had appreciably higher SI values. Nevertheless, the "undisturbed" watersheds still exhibited moderate channel instability. These results suggest that all channels are continually undergoing adjustment and that there is some level of naturally occurring background hydromodification within southern California watersheds, even in the absence of development.

**Table 5-9. Rapid Geomorphic Assessment**
*Results of evaluation process designed to assess the stability of a stream site*

| | Site | Stream Type | AI | DI | WI | PI | M | SI | Stability Class |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Topanga Canyon | AL(Ar) | 0.33 | 0.40 | 1.00 | - | 3 | 0.43 | A |
| 3 | Hasley Canyon | AL | - | 0.89 | 0.83 | 0.43 | 4 | 0.54 | A |
| 4u | Plum Canyon u/s | AL | 0.80 | 0.80 | 0.71 | 1.00 | 4 | 0.83 | A |
| 4d | Plum Canyon d/s | AL | 0.83 | 0.60 | 0.71 | 1.00 | 4 | 0.79 | A |
| 7u | Borrego Creek u/s | AL | 0.83 | 0.40 | 0.80 | 0.86 | 4 | 0.72 | A |
| 7d | Borrego Creek d/s | AL | 0.83 | 0.83 | 0.71 | 0.67 | 4 | 0.76 | A |
| 9 | Serrano Creek | RC | - | 1.00 | 0.83 | 0.43 | 3 | 0.75 | A |
| 10 | Santiago Creek | AL | 0.60 | 0.80 | 0.60 | 0.57 | 4 | 0.64 | A |
| 23 | Dry Creek | AL | - | 0.57 | 0.83 | 0.43 | 4 | 0.46 | A |
| 27 | Hick's Canyon | AL | - | 0.71 | 0.75 | 0.14 | 4 | 0.40 | T |

Explanation:

AI Evidence of aggradation
DI Evidence of degradation
WI Evidence of widening
PI Evidence of plan form adjustment
SI Stability Index (see interpretation of SI value below)

| SI Value | Interpretation | Comment |
|---|---|---|
| $0 \leq SI \leq 0.25$ | S - Stable | The morphologic features do not show evidence of progressive alteration and type and variance in the dimensions of morphologic features is within acceptable levels. |
| $0.25 < SI \leq 0.4$ | T - Transitional | The type and variance of observed morphologic features indicates that the stream channel is in or about to begin the initial stages of adjustment. |
| $0.4 < S \leq 1.0$ | A - In Adjustment | The type of morphologic features suggests that the channel system has been de-stabilized and is in the middle of adjusting to new conditions. |

## 5.8 Data Summary

The data collected for this study, both historical and field data, have been summarized and described in this section. More detailed presentations of this data are provided in Appendix A (land use, precipitation, stream flow, and historic surveys) and Appendix B (survey comparisons and channel materials). A basic assessment of the data including some general implications about the channel and watershed systems that they describe has also been provided. These serve more to describe the study sites and provide background and general findings based on the data collected.

# 6. CHANNEL RESPONSE

Results of the analysis of stream channel response to changes in watershed TIMP are presented in this section, followed by a discussion of the implications of these results for management purposes in Section 7. Analysis of channel response was based on an evaluation of the discernable changes in channel form and how they relate to measurable changes in watershed imperviousness (TIMP). Various channel metrics (measurements of channel form) are evaluated to establish these relationships. Summarized below are the results of channel-specific data evaluation and the connections between changes in channel morphology and the changes in watershed development (i.e. imperviousness). More detailed discussion and data on these evaluations are provided in Appendix C.

## 6.1 Stream Channel Morphology

Stream channel morphology was evaluated based on channel width ($W_{bfl}$), average channel depth ($d_{bfl}$), and cross sectional area ($A_{bfl}$, or the combination of width times average depth), and flow velocity ($V_{bfl}$). Width and cross sectional area are measured directly from the plotted cross sections derived through current and historic field surveys. Average depth was calculated from the measured data ($d_{bfl} = A_{bfl} / W_{bfl}$). Flow velocity was also calculated using channel slope ($S_{bfl}$) and estimates of roughness derived from sediment data collected during field surveys. These features were measured at the stage (water surface elevation) of the Dominant Discharge, also referred to as the "bankfull" stage (hence the various subscripts of "bfl"). Details of the selection of Dominant Discharge for use among the channels is given in Appendix C2.

The channel features for a specific stream type were plotted against the estimated Dominant Discharge ($Q_{bfl} = A_{bfl} * V_{bfl}$) to look for a correlation values that would indicate deterministic behavior. The following three relationships were established:

1. There is a logarithmic relationship between dominant discharge ($Q_{bfl}$) and channel width ($W_{bfl}$; Figure 6-1). The data used in this plot excluded the braided channel types (Sites 4d and 7d) and the canyon channel type (Site 9).
2. Dominant discharge ($Q_{bfl}$) is realated to cross sectional area ($A_{bfl}$) by a power function (Figure 6-2). The data set for this assessment included all of the sections for all of the study sites.
3. There is an inverse logarithmic relationship between the width to depth ratio ($W_{bfl} / d_{bfl}$) and the ratio of excess shear stress for the bed materials to the excess shear stress for the bank materials (Figure 6-3). The latter ratio expressed on the x-axis is a measure of the inherent ability of the channel bed and bank materials to resist the erosive forces associated with flowing water. The term "excess" in this case is the difference between actual calculated shear stress on the bed or bank and the critical shear stress required to move (or erode) particles. The full expression is provided in Appendix C3, along with an expanded discussion of the evaluation process. The correlation of these values is considerably lower than it is for the channel geometry components ($R^2 = 0.67$), but is surprisingly good considering the range of activities represented by this measure of channel shape.

The relationships between channel features and the Dominant Discharge (Figures 6-1 and 6-2) demonstrate a predictable or deterministic behavior in the channel geometry at these sites. As discharge increases, there is an expected increase in channel size. Comparing Figures 6-1 and 6-2 show that the initial channel response to increases in discharge is to widen; however, with increasing discharge, increased depth (i.e. downcutting) is the predominant response. The relationship of channel shape to excess shear stress (Figure 6-3) also establishes a good basis for the predictable nature channel form. The shear stress relationship also suggests threshold behavior for the widening or deepening of the stream channel. After a minimal level or bed and bank resistivity has been exceeded, the width-to-depth quickly declines (i.e. channel incision). All of these relationships provide useful techniques to fill data gaps in time series assessments of channel changes.

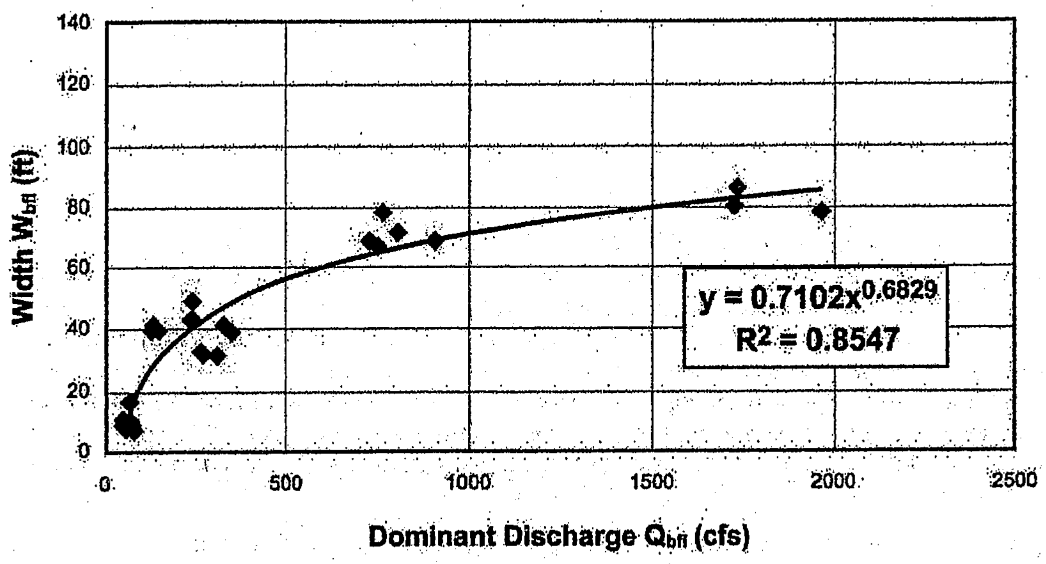



**Figure 6-1. Channel Width and Dominant Discharge**

## 6.2 Evaluating Changes in Stream Channel Condition

Natural stream channels exhibit changes over time in their geometry (width, depth, and slope) due to changes in environmental conditions. Various conceptual models exist that can be used to explain the state of a stream channel relative to an equilibrium condition, including steady state, dynamic equilibrium, and metastable equilibrium. The literature on this subject is quite large and the application of terminology has been somewhat inconsistent. Therefore, the terms and concepts discussed here in relation to conceptual models of channel adjustment are defined below.

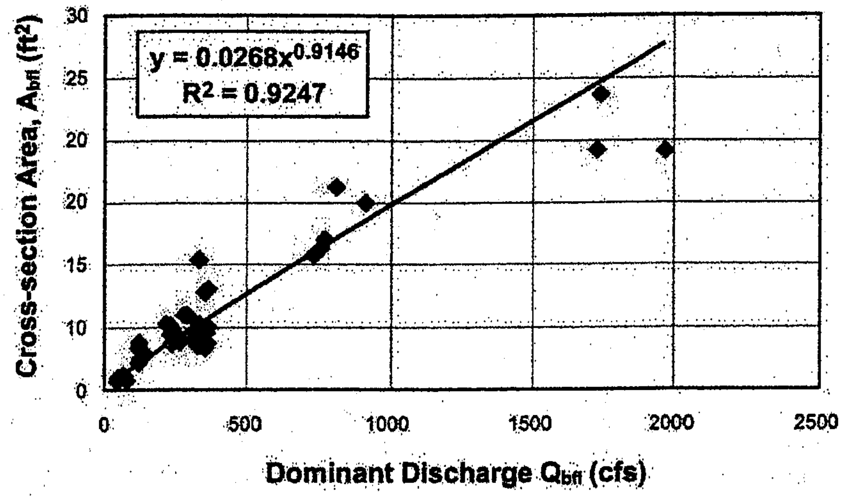



**Figure 6-2. Cross Section and Discharge**

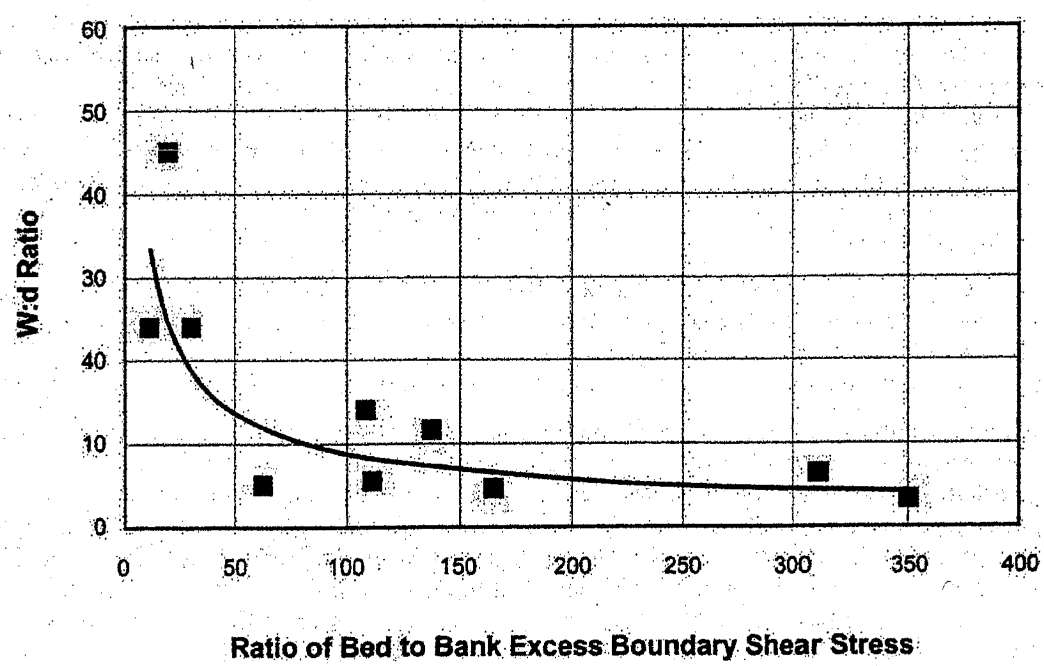



**Figure 6-3. Channel Shape and Resistance**

*Width to depth ratio as a function of the product of specific stream power and the ratio of bed to bank excess boundary shear stress*

- **Steady State.** Channel form components, including the width, depth, and slope, vary over time, but always within a definable range about a mean value that does not change over the period of time under consideration. Such a system is usually identified only for short time periods.

- **Dynamic Equilibrium.** Channel form components vary about a mean value that slowly changes over time. This type of condition usually can be identified for longer time periods than the Steady State condition.
- **Metastable Equilibrium.** Channel components also vary about a slowly changing mean value. However, this mean value can suffer rapid and dramatic change if a threshold is passed. Thus, the Metastable Equilibrium state is multiple periods of dynamic equilibrium separated by significant adjustment.
- **Statistical Stationarity.** Demonstration of a steady state condition through the application of statistical evaluation of one or more components of channel form.

In the present study the length of time represented by the data set is relatively short, which makes evaluating the system equilibrium a challenge. In addition, because this investigation is looking at artificially induced change in the equilibrium of these systems, it is important to be able to distinguish between internal (or natural) system change, and external (or artificial) change. The attempt to sort out the equilibrium status of these systems included the use of "control" sites where little to no development has occurred over the period of historic measurement of channel form.

Two of the control sites were Dry Canyon (Ventura County) and Hicks Canyon (Orange County). Each of these sites had multiple measurements at the same channel cross section over time periods of 3 years and 18 years respectively. Although both of these sites demonstrated periodic, or cyclical behavior in the adjustment of some channel geometry components (including $W_{bfi}$ and $A_{bfi}$), they also exhibited an abrupt change in the thalweg elevation that to-date does not appear to be reversing. Neither change appears to have resulted from excessive storm events or other external causes. Therefore, it appears that the studied channel systems in southern California are not in a steady state condition, and the statistical stationarity of this system (at least in terms of the thalweg elevation) cannot be demonstrated. In other words, even in the absence of external forces, there is a natural rate of change of stream channel depth over time (see also Appendix C3, Section C3.4).

Both the control and the developed sites experienced channel degradation (i.e. negative change in the thalweg elevation) over the period studied. The average degradation rate over the longer period of records was 0.12 ft./yr. for the control sites and 0.31 ft./yr. for the developed sites. It appears that one of the effects of increased TIMP is an increase in the *rate* of channel degradation.

In addition, the precipitation averages during the periods of change for the stream channel sites adjacent to these control sites differed in each area (see Section 5.2). The Ventura County and LA County data suggest that changes occurring at Hasley Canyon and Plum Canyon occurred during a period of lower than average precipitation. The data for Orange County suggests the opposite situation, with higher than average precipitation amounts occurring during the periods of channel change. However, the actual impact of these higher than normal rainfall amounts and stream flows (see Section 5.3) on the Orange County sites, does not appear to alter the conclusion that changes in TIMP were the primary cause of channel change, and not higher than normal rainfall. The most important argument for this assertion is that the channel conditions at nearby Hick's Canyon remained stable during this same period, even though it was experiencing a decrease in thalweg elevation. Thus the same rainfall conditions that were causing significant channel erosion at Borrego Canyon Wash and Serrano Creek, were not significantly altering the channel conditions at Hick's Canyon other than the thalweg elevation.

The fact that deterministic relationships have been demonstrated for a number of channel geometry components and for channel boundary resistance (as described earlier in Section 5), argues for these systems being at least in a dynamic equilibrium. Since statistical stationarity cannot be demonstrated, dynamic equilibrium is still possible and steady state is not likely. Furthermore, because the developed watersheds are undergoing imposed changes, and the stream channels are responding to this perturbation, significant adjustments are occurring in the general mean values of the system in its state of dynamic equilibrium. This suggests further refinement of the model to one of dynamic metastable equilibrium. More detailed discussion of this topic is provided in Appendix C3.

### 6.3 Stream Channel Response

Evaluation of channel enlargement requires multiple data points over a time sequence that includes the predevelopment condition (as the baseline or beginning point in time), the current condition (as the end-point), and one or more "historical" data points. The historical data points represent conditions that occurred along the time sequence between the baseline and the end point. In many cases the current conditions do not represent the ultimate end of the adjustment response (the ultimate end point). Therefore, the ultimate condition must be estimated, if possible, using specific and consistent techniques. A full description of the channel enlargement evaluation process is provided in Appendix C4. A brief summary of the procedure follows:

1. Collect available data and decide whether the data coverage is adequate.
2. Establish the baseline time marker (the actual date, or a time of $t_0$) and channel baseline condition ($A_{pre}$) for each site.
3. Evaluate all historical points between the baseline time marker ($t_0$) and the present time ($t_{ext}$) to understand their condition. Decide whether a single response or multiple responses are occurring at each site.
4. Predict the ultimate condition of the channel at each site upon completion of the adjustment (assuming the existing condition is not the ultimate condition). Appendix C4 provides a discussion of the techniques for completing Steps 3 and 4 if the data set is incomplete.
5. Use the data output from Steps 2, 3, and 4 to construct the *relaxation curve* for each site.
6. Since all of the sites have varying amounts of change in their watershed with regard to TIMP, and this causes varying amounts of channel adjustment, an enlargement curve (defined below) is developed to understand and compare data. To do create the enlargement curve we must assume or predict values of the time it will take to reach the ultimate condition, and the value of that ultimate condition ($A_{ult}$), for each adjusting site.

Two important aspects of channel change are compared over time, (a) the change in thalweg elevation and (b) the change in channel cross section area for the bankfull stage. The availability of all of this data for historic and/or baseline conditions is not always ideal, so adjustments must be made to complete the evaluation. However, all of the data mentioned above, except the channel slope, can be calculated from surveyed cross sections.

Comparison of the cross-section area of the channel at the bankfull or Dominant Discharge stage ($Q_{bfl}$) at different points in time produces a ratio of channel cross section area ($A_{bfl}$) from a later period to the earliest, or baseline period. This comparison is termed the enlargement ratio ($R_e$), and takes the form of Equation [6.1].

$$(R_e)_{his} = A_{his} / A_{pre} \qquad [6.1]$$

where:

$A_{his}$ = Cross section area of the bankfull channel at an historical point in time (square feet).

$A_{pre}$ = Cross section area of the bankfull channel for the baseline condition (square feet).

Similar comparisons are made for the existing condition ($A_{ext}$) and the projected, ultimate condition ($A_{ult}$). The ultimate condition requires an estimation of channel metrics at the end of the adjustment period. None of these sites has reached its ultimate condition in response to the development that has occurred, as this can take several decades (see Appendix C4). Therefore, the ultimate channel condition, and the time it will take to achieve it, must be estimated. The amount of time required for the full adjustment to be completed is called the *relaxation period.* The plot of the adjustment process over time is called the *relaxation curve.* Data from the current study are plotted in Figure 6-4 along with a reference relaxation curve developed using data from urban stream channels on Austin, Texas, which have similar geomorphic and hydraulic conditions, but somewhat different precipitation patterns.

The data plotted on Figure 6-4 are the results of the current investigation with the curve developed for the Austin data. It appears that the changes occurring at the current study sites are still within the initial stages of adjustment, and thus too close to the increase in TIMP to effectively predict the complete adjustment process. Therefore, it is still premature to prepare a relaxation curve developed only with the southern California data from the study sites. In addition, some of the study site data, particularly for the Plum Canyon and Borrego Canyon Wash sites, are not typical of the enlargement data in general.

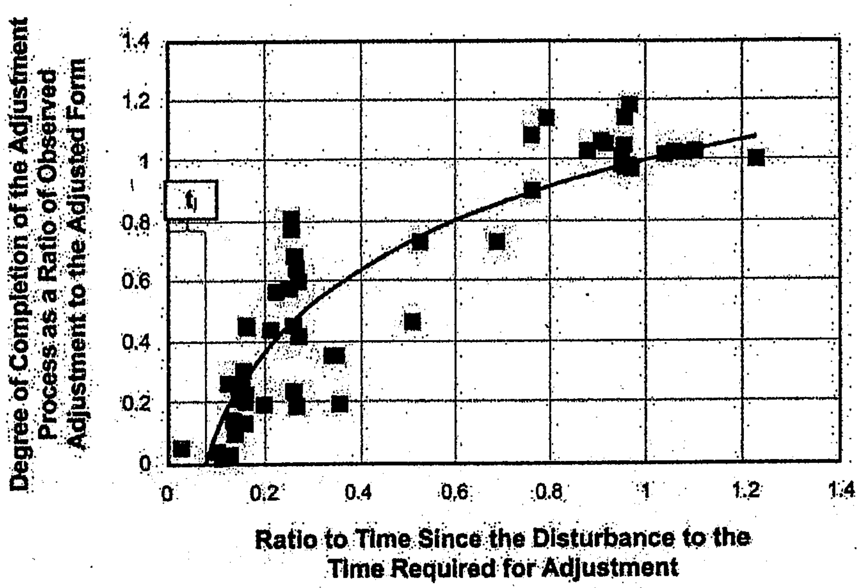



**Figure 6-4. Relaxation Curve and Study Data.**
*Curve developed for urban channels in the Austin, Texas area formed in alluvium. Data points shown are for the study sites in southern California.*

The Plum Canyon (LA County) and Borrego Canyon Wash (Orange County) sites are similar to each other and dissimilar to the other sites. Each of these stream channels had two sites, an upstream and a downstream site. On each stream the downstream site has a smaller channel and smaller Dominant Discharge than the upstream site, indicating a loss of flow downstream (i.e. a losing stream). In both cases the upstream sites showed a significant increase in channel size in response to the increase in TIMP, followed by a decrease in channel area. At Site 4u (Plum upstream) the channel cross section area initially increased more than 100% [$(R_e)_{his}$ = 2.22] and then decreased to a size only 43% greater than the baseline condition [$(R_e)_{ext}$ = 1.43] as recorded in the current survey data. At Site 7u (Borrego upstream) the enlargement ratio initially went to 1.37, declined to 1.25, increased to 1.47 and then decreased to 1.06 in the current survey. In neither case did the enlargement ratio continue to increase, albeit at a declining rate of increase, toward an expected ultimate value (as the curve in Figure 6-4 shows). In contrast, the other sites with developed watersheds (Sites 3u, 3d, 4d, 7d and 9) did show consistent increases in enlargement ratios.

A possible explanation for the changes observed at the upstream Borrego Canyon and Plum Canyon sites is suggested in a conceptual model proposed by Andrews (1979). His model identifies three phases of channel adjustment.

- The **First Phase** of Andrews' Three-Phase response model predicts straightening of the channel thalweg and destruction of the bed forms leading to homogenization of the bed materials and fluvial features in the longitudinal sense. This increases the slope and decreases channel resistance thereby effectively increasing the energy available in the watercourse to perform work.
- In the **Second Phase** of the adjustment process, Andrews' model predicts one of three responses: downcutting, widening or both downcutting and widening. The actual response will depend on the absolute resistance of the boundary materials as well as the relative resistance of the bed and bank materials at the least resistant bank toe stratigraphic unit (MacRae, 1992). The net effect of channel widening would only be temporary, however, as eventually the channel becomes too wide to support continued growth.
- The **Third Phase** would result in a new channel forming (incising) into the newly formed, extra-wide channel. Channel change from this point would then follow the more common response to increased flow and reduced sediment load with the typical enlargement of the channel to a new equilibrium position.

The current observations at the upstream Borrego Canyon and Plum Canyon sites are likely at the transition between the second and third phases of Andrew's 3-Phase model; the channel has constricted after initially enlarging significantly. The bank materials in the upstream Borrego and Plum reaches are highly erodable (mostly unconsolidated sands) while the bed may have been armored with cobbles prior to urbanization. Consequently, the resistance of the bank materials is very low relative to the bed materials as is the absolute resistance of the bank materials to the applied stress. Consequently, while there may have been some downcutting it is likely that the initial response was widening. Furthermore, overbank flows would have easily reworked the loose sands in the overbank area creating chutes and scouring out the wide swath of channel that was observed at the upstream sites.

Although the data from the current study are not adequate by themselves to develop a specific relaxation curve for southern California streams, they were used in conjunction with the established curve (in Figure 6-4) to develop an enlargement curve (Figure 6-5). The data for southern California streams forms a relationship very similar in shape to the enlargement curves developed for the larger database of North American streams. However, the database for southern California streams plots above the general line for the other data, suggesting that a specific enlargement ratio is produced at a lower value of impervious surface area in southern California than in other parts of North America. It is important to emphasize that the data for southern California streams are from systems in the initial stages of adjustment, and therefore are less reliable than they would be if the data were from a more advanced stage of adjustment.

Nevertheless, there are some important conclusions that can be drawn from the data of the current study.

- The channel systems studied here are very sensitive to external changes in the impervious areas within their watersheds. Increases on the order of 2% to 3% in TIMP have initiated increases in channel cross sectional area. The threshold of response for channel enlargement in southern California appears to be substantially lower than in other parts of North America.

- On the short time frame considered in this investigation (10 to 20 years) these systems are considered to be in a state of dynamic equilibrium. The control sites exhibit signs of active downcutting (thalweg elevation decreases) over time while maintaining stable channel morphology. This indicates that all channels are undergoing change; however, the rate of change may be different between streams that are subject to increases in peak flow and those that are not. Longer time series of analysis is necessary to more clearly define these relationships.

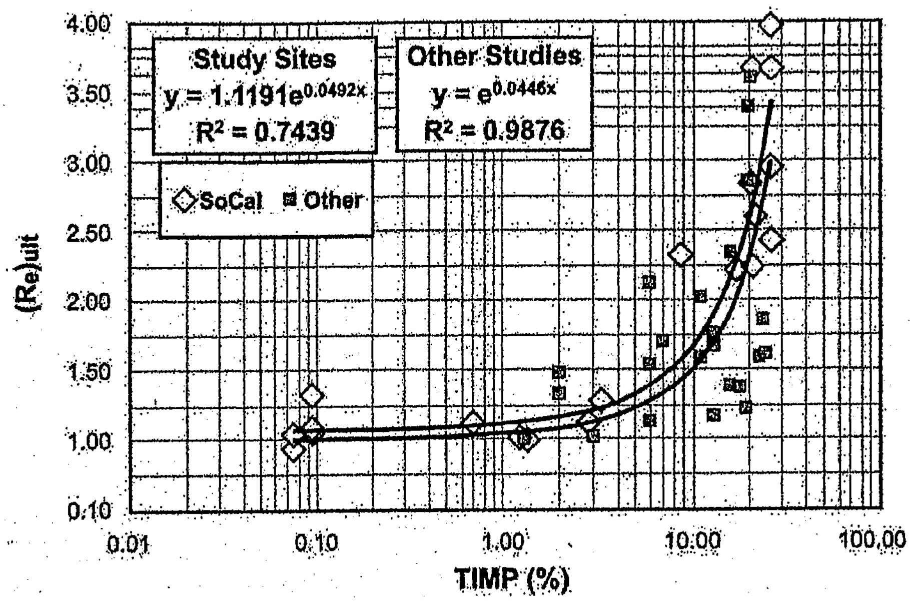



**Figure 6-5. Enlargement Curve for Southern California.**
*Upper curve and data points are for southern California channels in the current study. Lower curve is based on data from other locations in North America.*

- Because the measurement error is of the same order of magnitude as the sensitivity values, these systems should be considered to have zero tolerance for increases to TIMP values, and be managed accordingly. This includes adopting one or more of the following management strategies:

1. Zero tolerance for runoff increases (if not actually reducing runoff to below pre-development levels); or
2. Employ active management of stream channels to maintain or stabilize the stream channel condition and habitat; or
3. Establish a "no build" or "no disturb" riparian corridor to accommodate the expected channel adjustment response to the expected change in watershed imperviousness.

# 7. CONCLUSIONS AND RECOMMENDATIONS

The affects of urbanization on stream channels have been well studied in perennial systems in the humid regions of the U.S. The results of these studies are widely accepted, and demonstrate that increases of urban (or developed) areas within a watershed lead to increases in stream channel size (depth and/or width) and a decline in the diversity of aquatic species and the quality of aquatic habitat. The present investigation attempted to expand this understanding into ephemeral and intermittent stream channels in semi-arid climates. However, because many of the smaller stream channels in arid to semi-arid areas are ephemeral and intermittent, the present study focused solely on changes in stream channel morphology and did not address impacts to aquatic habitat.

The primary concerns about the affects of urbanization on natural stream channels in southern California, from a regulatory/management perspective, can be summarized as follows

a) How do semi-arid stream channels differ from humid area stream channels in their response to increases in impervious area?

b) How can effective controls be selected for minimizing the impacts from increases in impervious area?

c) Which situations and what conditions are appropriate for use of the identified controls?

The following subsections provide answers to these questions to the extent that the data generated by, and analyzed under, this investigation will allow.

## 7.1 Conclusions

The focus of this study was to relate changes in watershed development to observed changes in the morphology of the stream channel draining the watershed. The study sites selected were intentionally small (i.e. all less than 20 $mi^2$ and most less than 5 $mi^2$) since stream channels draining smaller watershed areas are most sensitive to changes in impervious cover. Ephemeral stream channels can be found in all climates, the main difference between regions is the size at which the contributing watershed area becomes large enough to support perennial stream flow. This size is dependent on a number of variables, but climate is a significant variable. In general, stream channels in arid areas remain ephemeral with larger catchment drainage areas than stream channels in more humid regions. This difference contributes to their increased sensitivity to changes in TIMP.

Based on the results of the present investigation, several principles of urbanizing ephemeral stream channels are suggested. The first principle concerns watershed area.

**Principle 1. CDA Size Focus.** The drainage area contributing runoff to a stream channel is a key characteristic for determining stream channel size. Ephemeral/intermittent stream channels are no different than perennial streams in this regard.

- Hydromodification from changes in impervious area are most recognizable in watersheds smaller than about 20 square miles.
- Watersheds in the present study with CDA < 15 $mi.^2$ are ephemeral, with one exception (Serrano Creek appears to have a nuisance base flow from surrounding residential areas).
- Management of impervious area and connected impervious area is most critical in the smallest watershed management units (CDA ≤ 2.5 square miles).

The results of this investigation suggest that the threshold for TIMP (total impervious area) at which changes in stream channel morphology would be expected is lower in the semi-arid sites that are typical of southern California than for comparably-sized sites on perennial streams in more humid areas. Based on the current data set the apparent threshold in the value of TIMP for initiating stream channel morphology change is between 2% and 3%. Similar threshold values for perennial streams generally are closer to 7% for the northeastern U. S. (Schueler 1998) and 10% for the northwestern U. S. (Booth 1997).

The sites in this investigation that experienced changes in their morphology all had relatively low resistance to bed and bank erosion. This leads to the second principle of urbanizing (and arid) ephemeral streams:

**Principle 2. TIMP Sensitivity** Ephemeral stream channels are also affected by change in total watershed imperviousness (TIMP). The ephemeral/intermittent stream channels of the arid to semi-arid study region in southern California appear to be more sensitive to such changes than are perennial streams in the literature.

- The threshold of ephemeral stream channels for exhibiting changes to stream channel morphology due to change in TIMP value, is between 2% and 3% change in the total impervious area for the watershed.
- The threshold of response will vary based on stream type. For example, ephemeral stream channels that are configured like Topanga Creek with highly resistant bed and bank materials are likely to have a higher TIMP threshold for stream channel change.

The form of a stream channel is a composite response (by its ability to resist erosion) to the cumulative applied forces of stream flow. The forces imposed on the stream channel result from its hydrologic and sediment regimes, the size and timing of flows and the stream channel form, particularly the slope of the stream channel, or energy grade. The resistance of the stream channel to the imposed erosive forces is dependent on the competence and cohesion of the materials forming the stream channel bed and banks. This relates both to characteristics of the stream channel form as well as the resistance of its bed and bank materials.

The stream channels studied in this project included control sites, where little or no watershed development had occurred, and developed (i.e. adjusting) sites, where changes in TIMP had occurred over a period of time. Some minimal rate of change in channel depth and area was observed in all sites (control and adjusting); however, the rate of change was greater in the developed sites than in the control sites. The control sites exhibited a state of dynamic equilibrium because downcutting was observed, but channel morphology did not change appreciably over time. The adjusting sites exhibited instability, as some significant change had occurred in one or more measure of channel morphology. These results demonstrate poor channel resistance to increased flow in all the adjusting channels except Topanga Creek. However, because this is a relatively small data set, generalizations made from the current data will have to be confirmed with a more extensive inventory of stream channel form, stream channel slope, and bed and bank material resistance for both ephemeral streams and perennial streams in the study area.

A key component of stream bank resistance, especially in smaller streams, is the vegetation present and the impact it has in providing resistance to erosion through root binding or energy dissipation. While the study sites had vegetation present to varying degrees, it did not appear to be a significant component of the stream channel stability, particularly at those sites experiencing changes in stream channel morphology. This probably has as much to do with climate, because the dry conditions in ephemeral stream channels in southern California persist for large blocks of time through the year, favoring a limited vegetative cover for banks, and hence less cohesive stream channel banks.

This leads to the third principle of urbanizing ephemeral streams:

**Principle 3. Stream Channel Resiliency is Low.** The small sample of ephemeral stream channels taken in this investigation whose morphology is changing, had relatively low resistance to erosion. However, further investigation is needed to verify and quantify any differences in stream channel resistance between ephemeral and perennial streams in southern California. The role of vegetation in stream channel resistance also needs to be better defined.

- It is suspected that ephemeral stream channels have a narrower range in resistance and resiliency than perennial streams, and that this is on the lower end of the resistance scale, however there is no conclusive proof of this in the results of the current investigation.

- The low impact of vegetation on stream channel resiliency appears to be a significant difference between ephemeral and perennial streams.

The management of increased stormwater runoff due to development must be concerned not only with the total volume of runoff but also with the flow peaks for individual flood events (both of which increase with increasing TIMP). If the results of the current study are representative of ephemeral stream channels in southern California, then it appears concern for both volume control and peak control should be exercised for control of hydromodification. Because these stream channels appear to be more sensitive to changes in TIMP (Principle 2) it follows that they would be very sensitive to increases in flow rates. Additionally, they appear to have a low resiliency, or resistance to erosion (Principle 3), so it would also follow that these stream channels are more susceptible to channel enlargement. Change in the flow rate would imply not only the peak flow rate but also the duration of time that erosive flows occur. Therefore, it would appear that maintaining the current regime (i.e. hydrograph matching) would be necessary to avoid stream channel enlargement.

This leads to the fourth principal of urbanizing ephemeral streams:

**Principle 4. Management Considerations.** As an extension of Principles 2 and 3, ephemeral stream channels are expected to be sensitive to both the larger flow peaks resulting from volume control, and the extended duration of erosive flows under peak control.

- In the absence of channel stabilization or other in-stream controls, retention methods are likely to be more effective than detention methods.

Management options and strategies to address these concerns are discussed further in Section 4.2 to explore the alternatives available to watershed managers.

Previous stormwater management investigations were primarily concerned with perennial stream channels. This investigation has looked at a small number of sites on ephemeral/intermittent stream channels in a very large region with significant diversity. In spite of a considerable effort to locate study sites with the broadest representation possible, the sites selected provide only a limited representation of that diversity. Still, these sites have provided some very useful results in characterizing ephemeral stream channels. Differences clearly exist between the ephemeral/intermittent stream channels of this study and the perennial stream channels in the literature in sensitivity to increases in TIMP and stream channel resiliency. Some of these differences have been better clarified by this study, while others have been identified for further investigation.

This investigation and its results should provide both the regulatory community and management personnel with insights into ephemeral/intermittent stream channel behavior and management options that were previously not available or elucidated.

## 7.2 Management/Regulatory Approach

Management of stormwater ultimately begins with a vision of how the drainage network and stream channel system should look and function. This will determine the opportunities and constraints possible for stormwater management. The vision must be realistic and flexible, and is not likely to be the same for all watersheds. The focus of this investigation has been on physical properties of the "natural" stream channel, its response to changes in watershed development, and management implications.

### 7.2.1 Management Objective

Once the vision has been established, stormwater management starts with the establishment of global goals and objectives for the watershed. From these goals and objectives will follow the specific objectives for local stream channel reaches and smaller subwatershed areas. If preservation (or re-establishment) of natural stream channel appearance and function is one of these specific, local objectives, the results of this study provide a modest start toward establishing some of the criteria needed to meet this objective. The classification system provided in Section 4 forms the basis for making informed decisions regarding the type and focus of stormwater management and stream channel maintenance applications. By focusing on maintaining a viable, "natural" stream channel (at least in form and function), management approaches include some form of runoff control (to lessen possible increases in the volume of water in the stream channel) and/or stream channel protection (to prevent stream channel erosion due to increased forces on the bed and bank materials). The relative effectiveness of these two types of management is represented in Figure 7-1.

### 7.2.2 General Approaches

Three general approaches for accomplishing the specified stormwater management objectives are described below. They involve a trade-off between runoff control, and stream channel protection.

**Natural Channel Design (NCD).** This management approach is concerned primarily with preserving the native (and stable) condition of the stream channel reach under consideration. Because the emphasis is on preserving existing functions, this approach precludes in-channel activities that are not created using materials that are not native to that location and emphasizes surface runoff controls as the primary management tool. Allowable development within the contributing watershed can only be tolerated to the threshold level before surface runoff control must be implemented. The threshold for a watershed will depend on the type of stream channel and the nature of the stream channel slope, soil characteristics and bedrock in the watershed. For example, a stream channel with highly resistant bed and banks (like Site 1, Topanga Creek) will be able to accommodate a significantly higher level of change without a meaningful adjustment in stream channel morphology. Other stream channels (like the remaining study sites) can only tolerate a change in TIMP of between 2% and 3% above the "natural" condition of the pre-disturbed watershed. Therefore, zoning and building density restrictions to encourage low-impact, or "smart" development will be very important with this approach, as well as runoff controls.

**Geomorphologically-Referenced River Engineering (GRRE).** The goal of this management approach is to preserve the appearance of natural stream channel function to the greatest extent possible while limiting instability in stream channel morphology. Geomorphic principals are used to design a stable stream channel given the expected hydrologic and sediment regimes (which will be different than the pre-disturbed state). The stream channel is re-shaped to this design using a minimum of hard, engineered structural elements within the stream channel so that the natural appearance is preserved while the new stream channel form can remain stable. However, both surface runoff and in-channel controls are required to maintain the hydrologic and sediment regimes for which the new stream channel is designed. Allowable development that can be tolerated under this approach has fewer restrictions than the NCD approach in that the new stream channel is designed to accommodate flows that are larger than the flows that shaped the stream channel under the natural conditions of the watershed prior to development. None-the-less, surface runoff controls eventually become just as critical to the stability of the new stream channel design, as it maintains semi-autonomous behavior. In-stream controls are employed to the extent they are needed, and are not necessarily created with native materials.

**Traditional River Engineering (TRE).** The goal of this management approach, also referred to as "hard-lining," is to create the most efficient conveyance system possible for stormwater, and provide the greatest degree of protection for the bed and banks of the stream channel that provides stormwater conveyance. The stream channel system is engineered to accommodate flows up to the design storm level, whatever that may be, and is protected by hard-lining the bed and banks. Surface runoff controls are much less important under this approach than they are under the NCD or GRRE approaches.

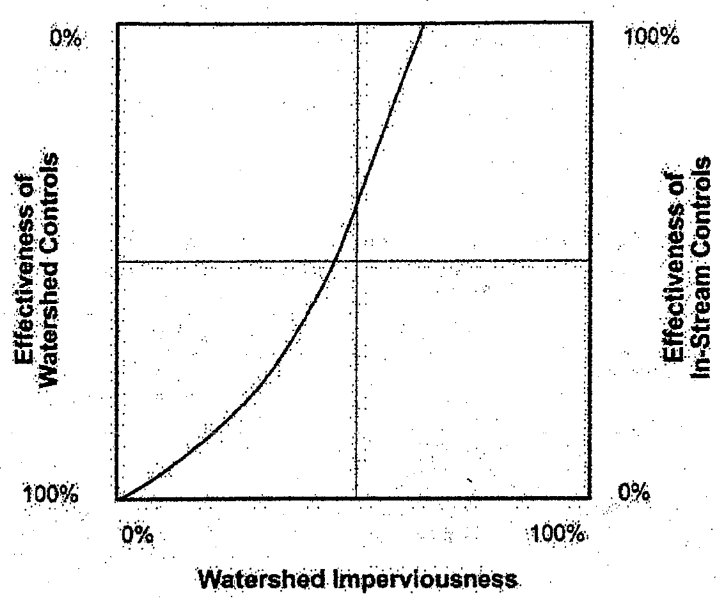



**Figure 7-1. Effectiveness of Stormwater Management Control Strategies**

Management approaches are selected so that they match the general goals and objectives for the watershed, as well as the specific objectives established for the stream channel reach in question. Because this investigation is concerned primarily with natural stream channel form and function, it focuses only on stormwater quantity and sediment load as it relates to stream channel activity, and is not directly concerned with water quality. There are a variety of best management practices (BMPs) available for controlling stormwater quantity, and a number of sources for obtaining information about these practices (EPA 1999, 2002, Mays 2001, WEF 1992). Controlling runoff can be organized into three general areas of control (source control, conveyance system control, and centralized control). Specific practices that illustrate these areas are listed in Table 7-1a. In-stream management practices also fall into multiple areas (grade control, sediment regime control, and bank stabilization). Some specific practices are listed in Table 7-1b. These tables list representative stormwater management options, but are not intended to be exhaustive lists.

### 7.2.3 Management Strategies

A general framework for assessing stormwater management strategies is presented in Table 7-2, which describes the applicability of four management strategies. The strategies are based on the current amount of development (i.e. TIMP) in a watershed and the expected stream channel stability. Functional relationships between these strategies, the management approaches discussed previously in this section, and the stream channel type classification system presented in Section 4 of this Technical Report are explored further in the discussions of these strategies presented below.

**Preservation.** The strategy for watersheds that have relatively little development and therefore a low percentage of impervious area is to take advantage of the opportunity to maintain or preserve a stable stream channel system. The recommended management for these watersheds is to first to consider NCD, as this is likely to be one of those rare occasions where NCD can be effective. The stream channel in its existing form is considered desirable and worth retaining. The stream channel is also considered to be a metastable system where change in stream channel form under natural conditions is considered acceptable over the planning horizon of 100 years. Management efforts are based almost entirely on surface runoff control with limited in-stream actions.

**Table 7-1a. Stormwater Management Practices**

| Focus | Objective | |
|---|---|---|
| | Retention | Detention |
| Source Control | • Dry well<br>• French drain<br>• Cistern<br>• Rain barrel<br>• Bioretention | • Detached downspouts<br>• Vegetated areas |
| Conveyance System Control | 4. Porous pavement<br>5. Channel diversions | 6. Rural drainage profile<br>7. Grassed swales<br>8. Stream Corridor Buffer zones<br>9. In-line detention<br>10. Reconnecting channel to the floodplain |
| Centralized Control | • Infiltration basin<br>• Retention basin | • Constructed wetlands<br>• Detention basin |

**Table 7-1b. In-Stream Management Practices**

| Focus | Practices | |
|---|---|---|
| | Soft Engineering | Hard Engineering |
| Grade Control | • Riffle<br>• Boulder clusters | • Drop structures<br>• Channel lining |
| Sediment Regime Control | • Pool<br>• Sediment introduction | 11. In-line detention<br>12. In-line sediment trap |
| Bank Stabilization | • Grading and vegetation of stream banks<br>• Vegetated gabions | • Riprap<br>• Rock gabions<br>• Pavers<br>• Channel lining |

**Restoration.** Watersheds with greater amounts of impervious area require management focused on bringing an unstable stream channel system back into a stable situation. Part of the management effort, ultimately, is to decide on an acceptable level of development for the watershed. Although the stream channel is destabilized, it can be restored to pre-disturbance form through control of the sediment-flow regime and in-stream works strategically located for grade control. Once provided with the right balance of control, the stream channel is able to restore itself through its own means. Erosion control is still primarily managed with surface runoff controls, although the emphasis on in-stream measures has increased to include localized sites and unstable and incised stream channel reaches.

**Rehabilitation.** Watersheds with significant impervious areas that are still manageable in total amount can have seriously degraded stream channels that are highly unstable and require significant effort to bring the stream channel back into a new, and stable, condition. The stream channel cannot be restored to its pre-disturbance form due to irrevocable changes to its form. However, the stream channel can be modified through a combination of surface runoff and in-stream works in accordance with the vision for the stream channel-valley system. Erosion control is based on matching the morphology of the stream channel with the new sediment-flow regime established for the stream channel based on implementation of a preferred SWM Alternative. SWM measures a required for new development and retrofit of existing developments. The emphasis on in-stream measures has increased to include localized sites and all unstable stream channel reaches.

**Table 7-2. Stormwater Management Strategies**

| Strategy Name | Applicability | Description |
|---|---|---|
| Preservation | Stable Channel<br>TIMP ≤ 6% | Stream channel is expected to be stable; Effort will be to keep it stable. |
| Restoration | Unstable Channel<br>6% < TIMP ≤ 10% | Stream channel is likely to be experiencing some instability (increase in capacity, change in hydraulic geometry values, etc.); effort will be correct changing inputs and nudge stream channel back to normal conditions |
| Rehabilitation | 10% < TIMP ≤ 20% | Stream channel probably has experienced irreparable changes (not able to restore "normal" conditions); effort will be to create a new (and maintainable) "natural" stream channel configuration. |
| Stabilization | 20% < TIMP | Stream channel has become extremely unstable and is on the verge (or in the middle) of significant morphological changes; effort will be to stabilize conditions with any means necessary and prevent excessive change. |

**Stabilization.** The worst case is in a watershed with levels of impervious area that are so high the focus of stream channel management must be on stabilizing a situation that will only get worse if nothing is done to address the stream channel erosion. The stream channel has become entrenched and the valley is confined by development, floodplain fill, and/or infrastructure encroachment. Instability is systemic to the majority of the main stream channel and erosion threatens property and infrastructure. Further adjustment of the stream channel is anticipated and will exacerbate the problem. Surface runoff controls for new developments and retrofit options for existing developments can achieve significant reductions in erosion potential. However, surface runoff management is not sufficient to stabilize the stream channel that is undergoing valley formation and susceptible to catastrophic failure during rare flood flow events. In-stream works are required to reconnect the stream channel to its floodplain, arrest the down-cutting process and stabilize the stream channel. Due to encroachment of development into the floodplain and infrastructure located within the valley, lateral migration of the stream channel may not be desirable. In this case GRRE at TRE approaches may be required, and these approaches may have no alternative except to hard-line the stream channel. In this situation surface runoff controls become redundant from an erosion control perspective. However, surface runoff control measures may be necessary for water quality or flood hazard issues. Surface runoff controls may also be required to meet the long-term vision for the watershed as the urban landscape reshapes itself through in filling and redevelopment.

### 7.2.4 Implementation of Management Strategies

Selection of a management strategy is dependent upon the extent to which a stream channel has been impacted by development within the watershed. The first step in implementing a management plan requires local communities to inventory and characterize each channel segment. This may result in a single stream having one or more stream segments with each of the four management goals. Therefore, land use controls and in-stream practices would vary based upon the established strategy for that particular stream segment. Table 7-3 summarizes the criteria and methods that could be used by communities to manage their stream networks.

Table 7-4 summarizes the various management approaches discussed earlier and shows linkages with implementation strategies that are appropriate for a given channel type and degree of TIMP. This table is based on practical, nationwide experience in stormwater management implementation that has been tailored for consideration in the southern California setting. In addition to this table, there are a three general strategies which should be considered when attempting to manage increases in peak flow:

1. **Limit Impervious Area.** Although the focus of this study was necessarily on TIMP, disconnecting impervious areas from the drainage network and adjacent impervious areas is a key approach to protecting channel stability. Utilizing this strategy can make it practical to keep the effective impervious cover (i.e. the amount hydrologically connected to the stream) equal to or less than the identified threshold of 2-3%.
2. **Control Runoff.** Hydrograph matching is not recommended for a single "design" storm with a specific return period, but rather for a range of return periods from 1 year to 10 years. Accomplishing such hydrograph matching will be challenging, and undoubtedly require a combination of techniques to prevent (retain), as well as to delay or attenuate (detain) runoff and/or stream flow.
3. **Stream Channel Movement.** Allow the greatest freedom possible for "natural stream channel" activity. This includes establishing buffer zones and maintaining setbacks to allow for channel movement and adjustment to changes in energy (associated with runoff). However, where in-stream controls are required consider all potential management options.

It is important to keep in mind that the choice of a management approach or approaches should be dictated by the strategies that are appropriate given the conditions of each stream reach and its contributing watershed. Consequently a suite of management approaches may need to be applied to provide a comprehensive solution to managing increases in peak runoff.

### 7.3 Applicability

Impacts to stream channels resulting from changes within the contributing watershed area, such as development and increased impervious area, are generally viewed as negative. Although no positive impacts were identified at any of the study sites, positive results are possible. The best example of this would be a stream reach that has an excess sediment load prior to development (i.e. an aggrading reach). Increased runoff and stream flow resulting from development could increase the carrying capacity of the stream enough to accommodate the excessive sediment load, thus producing a stable reach.

In order to relate the measurable changes in stream channels to changes in development, a measurable variable for development must be identified. The most commonly used value to represent development changes has been the areal extent of impervious area. This can be measured, laboriously, from maps and aerial photographs, or it can be estimated from existing land use maps with accepted conversion values. The latter method provides an estimate of the total impervious area (TIMP) in a watershed. A more accurate assessment of the actual impacts from development would come from the use of "connected impervious" area, or "CIMP" (also termed FRIMP). However, CIMP cannot be estimated as easily or effectively from land use data as can TIMP. CIMP must be carefully measured or delineated using detailed aerial photographs and (if available) detailed maps such as development plot plans or municipal parcel maps combined with extensive ground-truth checks. This is possible, though difficult, for current conditions, but it becomes much more difficult (if not virtually impossible) for historical conditions where ground-truthing is not possible. The degree of difficulty in calculating CIMP values and the scarcity of CIMP values in previous studies led to the decision to use TIMP values in the current investigation rather than CIMP values.

## Table 7-3. Implementation of Recommendations

| Management Goal | Management Strategy | Role of Local Government | Funding | Implementation Approach |
|---|---|---|---|---|
| NCD – Preservation<br><br>Stable Channel<br><br>0% ≤ TIMP ≤ 6% | Minimize Impervious Area<br><br>Maximize Infiltration<br><br>Preserve Environmentally Sensitive Areas | Land use planning<br><br>Zoning restrictions<br><br>Develop design standards for "smart growth" | Private developers | Inventory stream characteristics<br>Complete assessments of individual watersheds<br>Complete land use planning<br>Preserve environmentally sensitive areas<br>Establish stream channel/valley buffer zone<br>Develop "smart growth" design standards that<br>• Maintain "natural" shear stresses and hydroperiod of watershed.<br>• Post-development runoff volumes to closely equal pre-development runoff volumes<br>• Post-development peak rate of runoff < pre-development peak rate of runoff<br>Implement riparian vegetation planting/ management program<br>Monitor field conditions |
| NCD – Restoration<br><br>Unstable channel<br><br>6% ≤ TIMP ≤ 10% | Minimize addition of new Impervious Area<br><br>Maximize infiltration<br><br>Preserve strategic environmentally sensitive Areas<br><br>Restore "natural" hydroperiod<br><br>Restore natural characteristics of stream channels | Land use planning<br><br>Zoning restrictions<br><br>Develop design standards for "smart growth"<br><br>Restore natural characteristics of stream channels | Private developers<br><br>Public capital improvements | Inventory stream characteristics<br>Complete watershed assessments<br>Complete land use planning<br>Preserve environmentally sensitive areas<br>Establish stream channel/valley buffer zones<br>Develop "smart growth" design standards<br>• Maintain "natural" shear stresses and hydroperiod of watershed.<br>• Post-development runoff volumes to closely equal pre-development runoff volumes<br>• Require post-development peak rate of runoff to be less than pre-development peak rate of runoff<br>Implement riparian vegetation planting/ management program<br>Develop design criteria to retrofit existing development to mitigate increases in runoff volume and peak discharge rates<br>Plan, design and implement projects to retrofit existing development.<br>Limit in-stream works (localized erosion problems)<br>Monitor field conditions |

**Table 7-3 (continued)**

| Management Goal | Management Strategy | Role of Local Government | Funding | Implementation Approach |
|---|---|---|---|---|
| GRRE – Rehabilitation<br>Unstable channel<br>10% ≤ TIMP ≤ 20% | Preserve existing hydroperiod<br>Stablize stream channels | Development of design standards for runoff peak and volume controls<br>Stablize stream channels | Private developers<br>Public capital improvements | Inventory stream characteristics<br>Develop design criteria for a new development to maintain existing runoff volume and peak discharge rates<br>• Post-development peak rate of runoff = or < pre-development peak rate of runoff<br>Plan, design and implement BMPs to retrofit existing development.<br>Preserve vegetative cover of stream channel and buffer strips along stream channel<br>Substantial In-stream works to stabilize stream channel<br>• Establish grade controls<br>• Use bioengineering techniques to stabilize stream channels |
| TRE – Stablization<br>Unstable channel<br>20% ≤ TIMP | Stablize stream channels | Stablize stream channels | Public Capital Improvements | Inventory stream characteristics<br>Maximize storage of stormwater runoff to reduce in-stream peak discharges<br>Channel hardening & grade controls<br>• Maximize use bioengineering techniques to stabilize stream channels<br>• Maximize use of "natural" materials to harden Stream channels<br>• Preserve vegetative buffer strips along stream channel<br>Flow Diversions |

In addition to concern over physical changes to stream channels (hydromodification) that result from increased impervious areas, impacts to habitat can also be significant. Natural stream channels offer some of the best opportunities in the southern California region for threatened and endangered bird species to avoid the pressures of development. Stable riparian zones can also support native plant species effectively. Such habitat is predicated on conditions remaining stable within the stream channel. Adjustment of plant and animal species to unstable conditions within the stream channel would require a separate, study. A study of this type should focus on the expected adjustments to various types of stream channel changes (widening, deepening, loss of soil, etc.) by a variety of biotic communities. The current study had to necessarily focus on understanding the physical system while attempting to understand the relationships of change within it.

Although stream flow records were available for only 2 of the 10 study sites, all of the stream gage records obtained were used primarily for establishing generic flow frequency relationships and return periods. This can be effectively accomplished (and was in this study) using nearby gage data. Therefore, the lack of specific gage data for each site is more a concern for convenience rather than reliability of results. Also, measuring stream flows for specific storms before and after development and relating that to changes in impervious area would be very helpful data for this investigation. However, in watershed studies as in much of scientific endeavor, there is always a gap between the ideal data set and the actual data set. The relation that was possible to measure compared stream channel changes (that resulted from changes in discharge) directly to the changes in impervious area. This did not provide the ideal comparison (impervious area to stream flow, stream flow to stream channel change) but it does provide a quantifiable relationship between stream channel change and impervious area change.

### 7.4 Study Limitations

The charge of this study, the defined objectives, and the adopted approaches were all very ambitious. However, the need for data on these types of systems in this environmental setting is great, and aim was therefore to maximize results for the available resources. Thus, the results should be recognized as preliminary.

This study attempted to define several complex relationships involving stream channel response to watershed change using a modest data set that covers a relatively short period of time. Because there are many variables that affect the complex relationships between TIMP, runoff, and geomorphic response in stream channels, the study design attempted to limit the potential influences of certain variables to better evaluate the response of others. However, in reality it is difficult to achieve the desired control of variables that is required for definitive results in a study of this type. Consequently, it is important to be aware of the following points while assessing the results of this study.

- The data gathering and assessment requirements of this project included three major efforts that each could have been addressed as stand-alone investigations. Stream channel classification, evaluation of Dominant Discharge, and assessment of form and process of streams located in urbanizing watersheds of a semi-arid region could each have been a significant investigative effort on their own. Therefore, the analytical effort was great relative to the data set generated.
- The scale of the study region is very large compared to the actual area included in the study. The size of the study region, excluding the interior drainage areas, is nearly 6,300 square miles. The total watershed area covered by the sites used in this study is less than 33 square miles.
- The nature and response of watersheds in drylands is generally different than watersheds in humid areas. Dryland streams have fewer stream flow events and the importance of the flows from the last storm event is greater (Graf 1988). Knowing the magnitude of the latest flood event is important for interpreting the channel features measured after that event. However, in all cases, the field measurements of channel features did not follow a wet season with significant storm events, and thus are considered representative of the lower range of more normal events in these systems.
- Although a sizeable effort went into gathering data for this study, a relatively small data set was generated and used to evaluate channel response. Therefore, compelling as the results of this study may be, they must be considered preliminary.

### 7.5 Additional Research Needs

There is a large body of research into the effects of urbanization on increases in peak flow from regions of the county with wetter climates. However, this information is nearly absent for semi-arid regions, like southern California. This investigation is one of the first to assess the response of ephemeral/intermittent stream channels in an arid region with changing hydrology due to urbanization of the watershed. This is a common condition throughout the six counties of the study area that grew at a rate of more than 12% between the last two censuses. Communities are increasingly concerned about the damage to the environment and to property but are uncertain as to how to make sound management decisions to control the situation. This investigation has identified a number of principles that appear to characterize the relationship between urbanization and the stability, or lack of stability, of ephemeral/intermittent stream channels. However, the investigation included a very limited number of streams. Therefore, it is recommended that future investigations be conducted to confirm and expand the understating of the unique processes involved.

(A) Survey stream channels in the study area with reconnaissance or remote sensing techniques to identify and classify the critical "natural" stream channel reaches that still remain in this region, and help focus management efforts and prioritize future research.

(B) Measure stream channel form, stream channel slope, and bed and bank material resistance for both ephemeral streams and perennial streams in the study area that fall into the category of critical "natural" stream channel reaches. This could include streams and rivers in the study region with watersheds greater than the size limits recommended for the classification system here.

(C) Study USGS and county stream gage data that span the period of urbanization in various locations throughout the study region to establish quantitative values for increased flows. Tie back to percent change in impervious area for this time period. Quantitatively assess whether relationships exist that could predict "effective rainfall" levels (the minimum precipitation needed to produce an "effective" flow in the stream channel) based on watershed size and TIMP

(D) Investigate in greater detail the measurement or estimation of impervious area through various methods and establish a correlation between them. This will create a common set of assessment values that would allow the use of older photographs and newer digital imagery remote sensing techniques to overlap TIMP calculations for longer time periods.

(E) Identify more candidate sites for future studies. Establish a permanent set of sites that will be less likely to be affected by future development or stream channel "improvements." Use the long-term monitoring of these sites to quantify natural rates of change over various climatic cycles.

(F) Develop and test conceptual and/or predictive models for use in evaluating management strategies and specific management options in different watersheds and stream channel types.

(G) Broaden understanding of ephemeral stream channels in the six county region with additional characterization and study; perhaps extending into the truly arid (interior drainage) parts of this region.

(H) Resurvey the study sites within the current water year to capture the impacts on these stream channels from an excessively wet rainfall season.

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# Coastal Water Quality Impact of Stormwater Runoff from an Urban Watershed in Southern California

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Field studies were conducted to assess the coastal water quality impact of stormwater runoff from the Santa Ana River, which drains a large urban watershed located in southern California. Stormwater runoff from the river leads to very poor surf zone water quality, with fecal indicator bacteria concentrations exceeding California ocean bathing water standards by up to 500%. However, cross-shore currents (e.g., rip cells) dilute contaminated surf zone water with cleaner water from offshore, such that surf zone contamination is generally confined to <5 km around the river outlet. Offshore of the surf zone, stormwater runoff ejected from the mouth of the river spreads out over a very large area, in some cases exceeding 100 km$^2$ on the basis of satellite observations. Fecal indicator bacteria concentrations in these large stormwater plumes generally do not exceed California ocean bathing water standards, even in cases where offshore samples test positive for human pathogenic viruses (human adenoviruses and enteroviruses) and fecal indicator viruses (F$^+$ coliphage). Multiple lines of evidence indicate that bacteria and viruses in the offshore stormwater plumes are either associated with relatively small particles (<53 $\mu$m) or not particle-associated. Collectively, these results demonstrate that stormwater runoff from the Santa Ana River negatively impacts coastal water quality, both in the surf zone and offshore. However, the extent of this impact, and its human health significance, is influenced by numerous factors, including prevailing ocean currents, within-plume processing of particles and pathogens, and the timing, magnitude, and nature of runoff discharged from river outlets over the course of a storm.

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## Introduction

Oceans adjacent to large urban areas, or "urban oceans", are the final repositories of pollutants from a myriad of point and nonpoint sources of human waste (*1*). Pollutants are transported to the urban ocean by surface water runoff (*1–4*), discharge of treated sewage through submarine outfalls (*5*), wet and dry deposition of airborne pollutants (*6*), and submarine discharge of contaminated groundwater (*7*). Until recently, effluent from sewage treatment plants was often the primary source of urban coastal pollution, including nutrients, pathogens, pesticides, and heavy metals (*8*). However, pollutant loading from many sewage treatment plants has declined over the past several decades because of improvements in civil infrastructure (e.g., separation of the storm and sanitary sewer systems to prevent combined sewer overflows), pollutant source control, and disposal/treatment technology (*9*). As a result, surface water runoff, in many cases, has supplanted sewage treatment plants as the primary source of pollutant loading to the urban ocean (*3, 10*).

The focus of this study is the coastal water quality impact of surface water runoff during storms, or "stormwater runoff", from an urban watershed in southern California. The study was motivated by several considerations. First, beneficial use designations for the coastal ocean in southern California apply year-round and, consequently, watershed managers are legally required to develop stormwater management plans for reducing wet-weather impairments of the coastal ocean (*11*). The impact of stormwater runoff on coastal water quality is of particular concern in arid regions such as southern California because, on an annual basis, a large percentage (>99.9% according to Reeves et al. (*2*) and >95% according to Schiff et al. (*10*)) of the surface water runoff and associated pollution flows into the ocean during a few storms in the winter. Second, while recreational use of the coastal ocean in southern California is lighter in the winter, compared to the summer, winter ocean recreation is still very common, particularly among surfers who surf the large waves that often accompany storm events (R. Wilson, personal communication). Third, to the extent that particles in stormwater runoff are associated with pathogens and other contaminants, their discharge to the ocean during storms may serve as a source of near-shore pollution that persists long after the storm season is over (*10, 12*). Finally, in many urban watersheds in southern California and elsewhere, the flow of stormwater runoff is highly regulated by civil infrastructure (e.g., dams) designed to minimize flood potential and maximize water reclamation. As will be demonstrated later in this paper, the regulated nature of stormwater runoff implies that the ocean discharge of stormwater runoff from urban watersheds can occur days after the cessation of rain, when the potential for human exposure to pathogens by marine recreational contact is significant.

This paper describes how stormwater runoff from several major rivers in southern California, with particular focus on the Santa Ana River in Orange County, impacts coastal water quality, as measured by turbidity, particle size spectra, total organic carbon, fecal indicator bacteria, fecal indicator viruses, and human pathogenic viruses. The present study is unique in the combination of data resources utilized, including data and information from routine surf zone water quality and wave field monitoring programs, an automated in-situ ocean observing sensor, shipboard sampling cruises, and satellite sensors. Further, this is the first wet weather study to examine the linkage between water quality in the surf zone, where routine monitoring samples are collected



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sensors in southern California called the Network for Environmental Observations of the Coastal Ocean (NEOCO). The NEOCO sensor package contains an SBE-16plus CTD (Sea-Bird Electronics, Inc., Bellevue, WA) and a Seapoint Chlorophyll Fluorometer (Seapoint Sensors, Inc.). These instruments are mounted on a pier piling at a depth of approximately 1 m (below mean lower low water) and are programmed to acquire data at a sampling frequency of 0.25 $min^{-1}$.

**Surf Zone Measurements: Fecal Indicator Bacteria and Breaking Waves.** The concentration of fecal indicator bacteria in the surf zone was measured at 17 stations (black circles along shoreline in Figure 1) by personnel at the Orange County Sanitation District (OCSD). The stations are designated by OCSD according to their distance (in thousands of feet) north or south of the Santa Ana River outlet (e.g., station 15N is located approximately 15 000 ft, approximately 5 km, north of the Santa Ana River outlet). Water samples were collected 5 days per week (not on Friday and Sunday) from 5:30 to 10:00 local time at ankle depth on an incoming wave, placed on ice in the dark, and returned to the OCSD (Fountain Valley, CA) where they were analyzed within 6 h of collection for total coliform (TC), fecal coliform (FC), and enterococci bacteria (ENT) using standard methods 9221B and 9221E and EPA method 1600, respectively. Results are reported in units of colony forming units per 100 mL of sample (CFU/100 mL). Wave conditions, including both the direction and height of breaking waves, were recorded by lifeguards at the Newport Beach pier (near surf zone station 15S, Figure 1) twice per day, once at 7:00 and again at 14:00 local time.

**Offshore Measurements: Satellite Ocean Color Imagery.** The satellite images used in this study were collected by NASA's Moderate-Resolution Imaging Spectroradiometer (MODIS) instruments. These instruments operate onboard two near-polar sun-synchronous satellite platforms orbiting at 705 km altitude: Terra (since February 24, 2000) and Aqua (since June 24, 2002). Terra passes across the equator from north to south at ~10:30 local time, while Aqua passes the equator south to north at ~13:30 local time. As such, all the images were acquired within 2 h before or after local noon or between 18:00 and 22:00 UTC. The MODIS sensors collect data in 36 spectral bands, from 400 to 14 000 nm. We utilized bands 1 (250-m spatial resolution, 620–670 nm), 3, and 4 (500-m resolution, 459–479 and 545–565 nm, respectively) to produce "true color" (i.e., RGB) images, with band 1 used for the red channel, band 4 for the green channel, and band 3 for the blue channel. Using a MATLAB program, the 500-m green (band 4) and blue (band 3) monochrome channels were "sharpened" to 250-m resolution using fine details from the higher resolution red channel (band 1). Then, the contrast of each of these monochrome channels was increased to emphasize maximum details in the coastal ocean region of interest. Finally, all three monochrome channels (i.e., red, green, and blue) were combined to form a single true color image. In all, 16 satellite images from February 23 to March 5 were acquired and processed for this study; four of them were selected as most illustrative, on the basis of their quality and observed features. The timing of these satellite acquisitions relative to the storms and sampling periods is indicated at the top of Figure 2.

**Offshore Measurements: Sampling Cruises.** The offshore monitoring grid (red triangles in Figure 1) was sampled during three separate cruises on February 23, February 28, and March 1, 2004, coinciding with a sequence of storm events in late February 2004. Table 1 provides a summary of activities performed during each cruise. A short description of the offshore sampling and analysis protocols is presented here; details can be found in the Supporting Information for this paper. All offshore water samples were analyzed for salinity and fecal indicator bacteria, specifically, total coliform (TC), *Escherichia coli* (EC, a subset of FC), and enterococci bacteria (ENT), using the defined substrate tests known commercially as Colilert-18 and Enterolert (IDEXX, Westbrook, ME) implemented in a 97-well quantitray format; results are reported in units of most probable number of bacteria per 100 mL of sample (MPN/100 mL). A subset of the offshore water samples was analyzed for total organic carbon (TOC) by U.S. EPA Method 415.1, fecal indicator viruses ($F^+$ coliphage) by a two-step enrichment method (U.S. EPA Method 1601), and human pathogenic viruses (human adenovirus and human enterovirus) by real-time quantitative polymerase chain reaction (Q-PCR), nested PCR, and reverse-transcriptase (RT)-PCR using published protocols (*21–25*). Details on the PCR protocols used here can be found in the Supporting Information for this paper.

Coincident with the collection of the offshore water samples, temperature, particle size spectra, and light transmissivity were measured using an LISST-100 (laser in situ scattering and transmissometry) analyzer (Sequoia Scientific, Inc., Bellevue, WA). The LISST-100 estimates the particle volume per unit fluid volume ($\Delta V$) resident in 32 logarithmically spaced particle diameter bins ranging in size from $d_p$ = 2.5 to 500 $\mu$m. At least 10 replicates of the particle size spectra were collected at each offshore station. Following the recommendation of Mikkelsen (*26*), $\Delta V$ was taken as the median of all replicate measurements. The LISST-100 data are presented in this paper in one of three ways: (1) particle size spectra represented by plots of $\Delta V/\Delta \log d_p$ against log $d_p$, (2) the number of particles per unit fluid volume or total number concentration (TNC), and (3) the number-averaged particle size, $\bar{d}$. The last two parameters were computed from the particle size spectra as follows (*26, 27*):

$$\mathrm{TNC} = \sum_{i=1}^{32} \frac{6\Delta V_i}{\pi {d_{p,i}}^3} \quad (1a)$$

$$\bar{d} = \sqrt[3]{\frac{6}{\pi}\frac{\sum_{i=1}^{32} \Delta V_i}{\mathrm{TNC}}} \quad (1b)$$

## Results and Discussion

**Rainfall and River Discharge.** Over the period of study (February 18 through March 3, 2004), four rain events were recorded by the rain gauge on the Santa Ana River in the City of Santa Ana (black curve, top panel, top axis, Figure 2). The first event accumulated 16.0 mm of rain in the afternoon of February 21 ($RE_1$ in Figure 2), the second event accumulated 23.4 mm of rain in the afternoon of February 22 ($RE_2$), the third event accumulated 51.3 mm of rain in the evening of February 25 ($RE_3$), and the fourth event accumulated 6.8 mm of rain in the evening of March 1 ($RE_4$). The rain gauge located on the San Gabriel River in the City of Long Beach did not record $RE_2$ but recorded a fifth rain event on February 18 (red curve, top panel, top axis, Figure 2). The difference in rainfall recorded at the Santa Ana River and the San Gabriel River sites is a consequence of the spatial variability of rainfall near the coast (see Figures S1 and S2, Supporting Information, for NEXRAD maps acquired during $RE_1$ and $RE_2$). Records of stream discharge (in units of $m^3/s$) at the Santa Ana River and the San Gabriel River sites are also quite different (black and red curves, top panel, bottom axis, Figure 2). While rainfall and stream discharge are coupled at the San Gabriel River site (i.e., stream discharge increases shortly after locally recorded rain events, compare set of red curves in top panel, Figure 2), rainfall and stream discharge are frequently uncoupled at the Santa Ana River site. For example, the Santa Ana River discharge events $DE_3$ and $DE_4$ do not obviously correlate with records of local rainfall. Instead, these two discharge events can be traced to stormwater runoff generated from inland regions of the Santa Ana River watershed



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**TABLE 1. Summary of Analyses Performed during the Sampling Cruises**

| sampling parameters | methods | number of offshore sites sampled: February 23, 2004 | February 28, 2004 | March 1, 2004 |
|---|---|---|---|---|
| conductivity[a] | Thermo Orion162A or CTD (SBE-32) | 20 | 21 | 21 |
| temperature[b] | thermocouple w/ LISST-100 or CTD (SBE-32) | 20 | 21 | 21 |
| total coliform, *Escherichia coli*, enterococcus[c] | Colilert and Enterolert (IDEXX) | 20 (+2 sets of fractionated samples) | 21 (+6 sets of fractionated samples) | 21 |
| total organic carbon[d] | EPA 415.1 | 17 (+2 sets of fractionated samples) | | |
| human adenoviruses & enteroviruses[5] | nested PCR RT-PCR | 2 | 6 | |
| fecal indicator viruses ($F^+$coliphage)[e] | two-step enrichment | 2 | 6 | |
| particle size spectra | LISST-100 (light diffraction) | 20 | 16 | 21 |
| transmissivity | LISST-100 | 20 | 16 | 21 |

[a] Measured using a Thermo Orion 162A conductivity meter on February 23 and a CTD instrument (SBE-32) on February 28 and March 1. [b] Measured using a thermocouple bundled with an LISST-100 on February 23 and a CTD instrument (SBE-32) on February 28 and March 1. [c] Samples collected by UCI and analyzed by OCSD on February 23 and collected and analyzed by OCSD on February 28 and March 1. Fractionated samples collected and analyzed by UCI on February 23 and 28. [d] Collected by UCI and analyzed by Del Mar Analytical (Irvine, CA). [e] Carried out on the fractionated samples and measured using a real-time PCR for enterovirus and a nested PCR for adenovirus.

**Surf Zone Measurements: NEOCO Data.** Water level, salinity, temperature, and chlorophyll measurements at the NEOCO sensor, located on the end of the Newport Pier at the offshore edge of the surf zone, are presented in Figure 2 (second and third panels). The largest rain event ($RE_3$) and the largest discharge of stormwater runoff from the Santa Ana River ($DE_4$) occurred during a neap tide when the daily tide range was small (see quarter moon and water level measurements in the second panel, Figure 2). The other rainfall and stream discharge events occurred during periods of time when the daily tide range was larger, either during the transition from spring to neap tide ($RE_1$, $RE_2$, $DE_1$, $DE_2$, $DE_3$) or during the transition from neap to spring tide ($RE_4$, $DE_5$).

Salinity recorded at the NEOCO sensor is characterized by a series of low salinity events, relative to ambient ocean water salinity of 32.5–33.0 ppt (salinity events $SE_1$–$SE_6$, Figure 2). These low salinity events may be caused, at least in part, by stormwater discharged from the Santa Ana River (e.g., $SE_6$ appears to be related to $DE_4$). However, correlating discharge and the low salinity events is complicated by the fact that once river water is discharged to the ocean, its offshore transport is controlled by a complex set of near-shore currents (*28*). These near-shore currents, and their impact on the spatial distribution of stormwater runoff plumes, are explored in the next several sections. Temperature and chlorophyll records at the NEOCO sensor appear to be relatively unaffected by rainfall or discharge from the Santa Ana River. Surf zone temperature exhibits a diurnal pattern consistent with solar heating (i.e., temperatures are higher during the day and lower at night). Chlorophyll measurements indicate a bloom event occurred early in the study period (bloom event 1, $BE_1$), but this bloom event mostly dissipated prior to the rain and discharge events that occurred later. While the chlorophyll fluorometer was being maintained during this period, we cannot rule out the possibility that the downward trend in the chlorophyll signal is related to instrument fouling.

**Surf Zone Measurements: Wave Data and Along-Shore Currents.** Wave conditions, including the direction and height of breaking waves, were recorded twice per day by lifeguards stationed at the Newport Pier (surf zone station 15S, Figure 1). These wave data, which are plotted in the fourth panel of Figure 2, can be divided into five events, depending on whether waves approach the beach from the west ($WE_1$, $WE_3$, and $WE_5$) or from the south to southwest ($WE_2$ and $WE_4$). Because this particular stretch of shoreline strikes northwest–southeast (see Figure 1), waves approaching the beach from the west are likely to yield a down-coast surf zone current (i.e., directed to the southeast). Likewise, waves approaching the beach from the south are likely to yield an up-coast surf zone current (i.e., directed to the northwest) (*28, 29*).

This expectation is consistent with the salinity signal measured at the NEOCO sensor, which is located approximately 5 km down-coast of the Santa Ana River ocean outlet. The onset of low salinity event $SE_6$ at the NEOCO sensor coincides very closely in time with the change in wave conditions from $WE_2$ to $WE_3$ and a likely change in the direction of the surf zone current from up-coast to down-coast (Figure 2). Discharge from the Santa Ana River was particularly high during this period (discharge event $DE_4$ overlaps wave events $WE_2$ and $WE_3$). Hence, the onset of $SE_6$ was probably triggered by a change in the direction of wave-driven surf zone currents from up-coast during $WE_2$ to down-coast during $WE_3$ and a consequent down-coast transport of stormwater runoff entrained in the surf zone from the Santa Ana River during $DE_4$.

Employing the same logic, low salinity events $SE_3$–$SE_5$, which occurred during a period when waves were out of the



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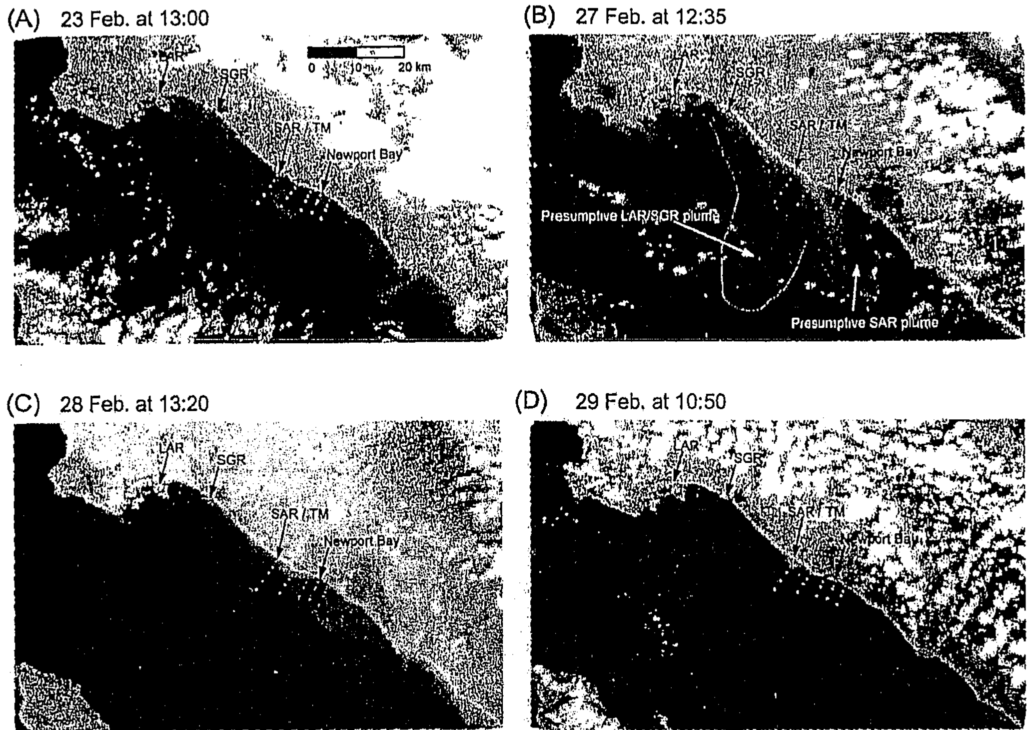


**FIGURE 3. MODIS Terra and Aqua true color satellite imagery of stormwater runoff plumes along the San Pedro Channel, California, with nominal spatial resolution of 250 m. Yellow dots indicate location of field sampling stations offshore of Huntington and Newport Beach; black arrows denote the Los Angeles River (LAR) outlet, San Gabriel River (SGR) outlet, Santa Ana River/Talbert Marsh (SAR/TM) outlet, and Newport Bay outlet. (A) MODIS-Aqua, February 23, 2004, at 21:00 UTC (13:00 local time), (B) MODIS-Aqua, February 27, 2004, at 20:35 UTC (12:35 local time), (C) MODIS-Aqua, February 28, 2004, at 21:20 UTC (13:20 local time), (D) MODIS-Terra, February 29, 2004, at 18:50 UTC (10:50 local time).**

wave events, surf zone water quality events, and offshore sampling cruises, is indicated at the top of Figure 2.

Generally speaking, in this collection of true color imagery the stormwater runoff plumes appear to be characterized by a band of turbid water turquoise to brown in appearance that is observed along the entire imaged region, although both cross-shelf and along-shore gradients in the color signature are evident. Following the rain events on February 21−22 (total of 39.4 mm, see $RE_1$ and $RE_2$ in Figure 2), a MODIS Aqua imagery from February 23 demonstrates the cross-shelf extent of the runoff plume to be variable, ranging from under 1 km in some places to more than 10 km offshore of the Los Angeles River and San Gabriel River (Figure 3A). At our study site, which is centrally located within this broad region, a distinct and apparently heavily particulate-laden runoff plume was observed in the vicinity of the Santa Ana River outlet and nearby station 2201 (see Figure 1 for numerical designation of offshore sampling sites). The Santa Ana River plume extended offshore past station 2203, with an apparent turn down-coast (i.e., southeast), continuing past stations 2104 and 2024. During this time, breaking waves were out of the south and the transport direction of fecal indicator bacteria in the surf zone was directed up-coast, opposite the apparent transport direction of stormwater plumes offshore of the surf zone (compare timing of satellite image 1 with $WE_2$ and fecal indicator bacteria events $TC_2$, $FC_2$, and $ENT_2$, Figure 2). It also appears that a portion of the Los Angeles River and the San Gabriel River stormwater plumes may have advected south and comingled with the Santa Ana River stormwater plume. Further south, offshore particulate loadings off the Newport Bay outlet (station 2001) do not appear to be as large as those off the Santa Ana River outlet.

A MODIS image on February 27 revealed two distinct plumes of considerable size and offshore extent (Figure 3B). This satellite acquisition preceded by 1 day the sampling cruise on February 28 (described in the next section), followed the large precipitation event on February 25−26 (total of 51.3 mm, see $RE_3$ in Figure 2), and followed the large discharge event from the Santa Ana River ($DE_4$, in Figure 2). The plume to the northwest in this image appears to be associated with the Los Angeles River or the San Gabriel River outlets, with an approximate areal extent of 450 km$^2$. The plume to the southeast appears to be distinct from the former plume and likely originated from the Santa Ana River outlet, with an approximate areal extent of 100 km$^2$ (the presumptive Los Angeles River, San Gabriel River, and Santa Ana River plumes are delineated by red lines in Figure 3B). The February 27 Santa Ana River stormwater plume is considerably larger in size than the one observed on February 23 (compare Figure 3A and 3B), consistent with the very large volume of water discharged from the Santa Ana River just prior to this satellite acquisition (approximately $4 \times 10^7$ m$^3$, see $DE_4$ in Figure 2). Further, the Los Angeles River, San Gabriel River, and Santa Ana River runoff plumes on February 27 differed from those on February 23 in that they penetrated farther offshore (30 km compared to 10 km) and thus potentially transported more sediments into the deep waters of the San Pedro Channel.

The jetlike appearance of the presumptive Los Angeles River, San Gabriel River, and Santa Ana River stormwater runoff plumes in Figure 3B has been observed elsewhere in the Southern California Bight, for example, off the Santa Clara River discharge (*4, 29*), and is potentially the result of inertia-driven flow. At the time of this second satellite acquisition, breaking waves out of the west, and along-shore transport in the surf zone and offshore of the surf zone, appear to be directed down-coast (compare timing of satellite image 2 with $WE_3$ and fecal indicator events $TC_3$, $FC_3$, and $ENT_3$).

Subsequent MODIS true color imagery on February 28 (Figure 3C) and February 29 (Figure 3D) indicates that both

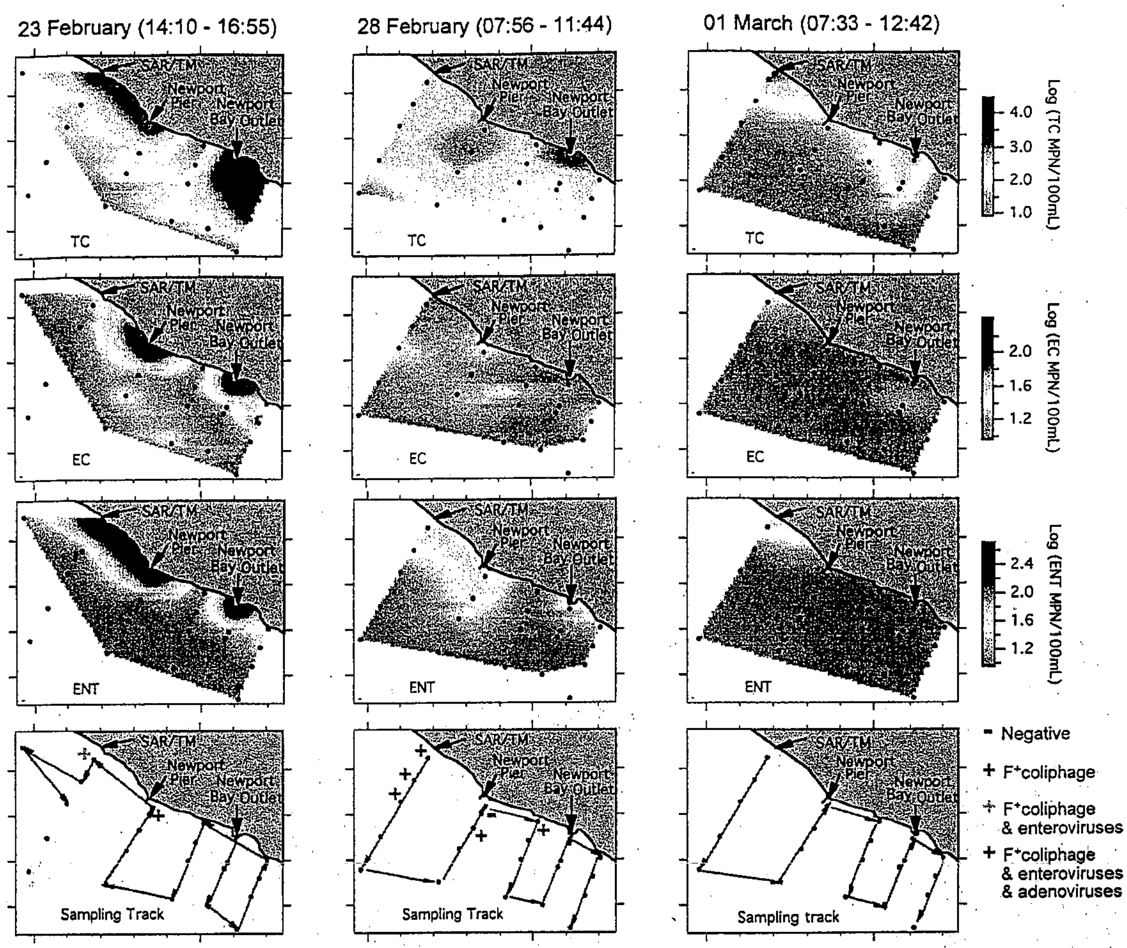


**FIGURE 5. Fecal indicator bacteria concentrations measured during the three sampling cruises. The bottom row of panels indicates the sampling track (blue arrows) and the detection of $F^+$ coliphage and human viruses. SAR/TM is an abbreviation for the outlet of the Santa Ana River and Talbert Marsh.**

more pronounced during the later cruise dates. For example, none of the samples collected during the February 28 and March 1 cruises exceeded state standards for fecal indicator bacteria, yet several of the samples collected from the surf zone during the same time period exceeded single-sample standards for one or more fecal indicator bacteria groups (compare concentrations measured during the second cruise date with $TC_3$, $FC_3$, and $ENT_3$ and concentrations measured during the third cruise date with $TC_4$, $FC_4$, and $ENT_4$, Figures 2 and 5).

**Offshore Measurements: $F^+$ Coliphage and Human Viruses.** Offshore samples tested positive for $F^+$ coliphage ($n = 8$, see Table 1), with the exception of a single sample collected on the February 28 cruise from offshore of the Newport Pier (blue, green, and red plus symbols, bottom panels, Figure 5). Human adenoviruses and enteroviruses were detected by real time Q-PCR, nested PCR, and RT-PCR in a sample collected from station 2201 located directly offshore of the Santa Ana River outlet during the February 28 cruise (red plus, middle bottom panel, Figure 5). The concentration of human adenoviruses in this sample is estimated to be $9.5 \times 10^3$ genomes per liter of water, which is approximately equivalent to 10 plaque forming units per liter of water, according to a laboratory study comparing Q-PCR results with plaque assay (*35*). Human enteroviruses were also detected in a sample collected directly offshore of the Santa Ana River outlet (station 2201) on the February 23 cruise (green plus, bottom left panel, Figure 5). While relatively few samples were tested for human viruses ($n = 8$), these results demonstrate that human viruses are present in surface water offshore of the Santa Ana River outlet following storm events, even when the fecal indicator bacteria concentrations are below state standards (e.g., station 2201 during the February 28 cruise, Figure 5). These results are consistent with previous observations that human pathogenic viruses and fecal indicator viruses persist longer than fecal indicator bacteria in ocean water (*36*). Direct PCR measurement of pathogenic viruses in highly turbid water is challenging because of PCR inhibition (*35*).

**Offshore Measurements: Relationship between Fecal Indicator Bacteria, Turbidity, and Number-Averaged Particle Size.** Turbidity has been suggested as a possible proxy for water quality (*37, 38*). However, on the basis of our offshore data, turbidity per se appears to be an inconsistent proxy for the concentration of fecal indicator bacteria. For example, during the February 23 cruise, there is good coherence between turbidity and TC, EC, and ENT concentrations off the Santa Ana River outlet and Newport Pier (compare transmissivity and TNC with fecal indicator bacteria results, left-hand column of panels, Figures 4 and 5). However, turbidity is low off of the Newport Bay outlet where the bacteria concentrations are particularly high. In addition, there are no consistently robust relationships between shipboard measurements of fecal indicator bacteria and shipboard measurements of TOC, temperature, or salinity (see Figure S4, Supporting Information). The number-averaged particle size, on the other hand, comes close to matching the along-shore spatial pattern of fecal indicator

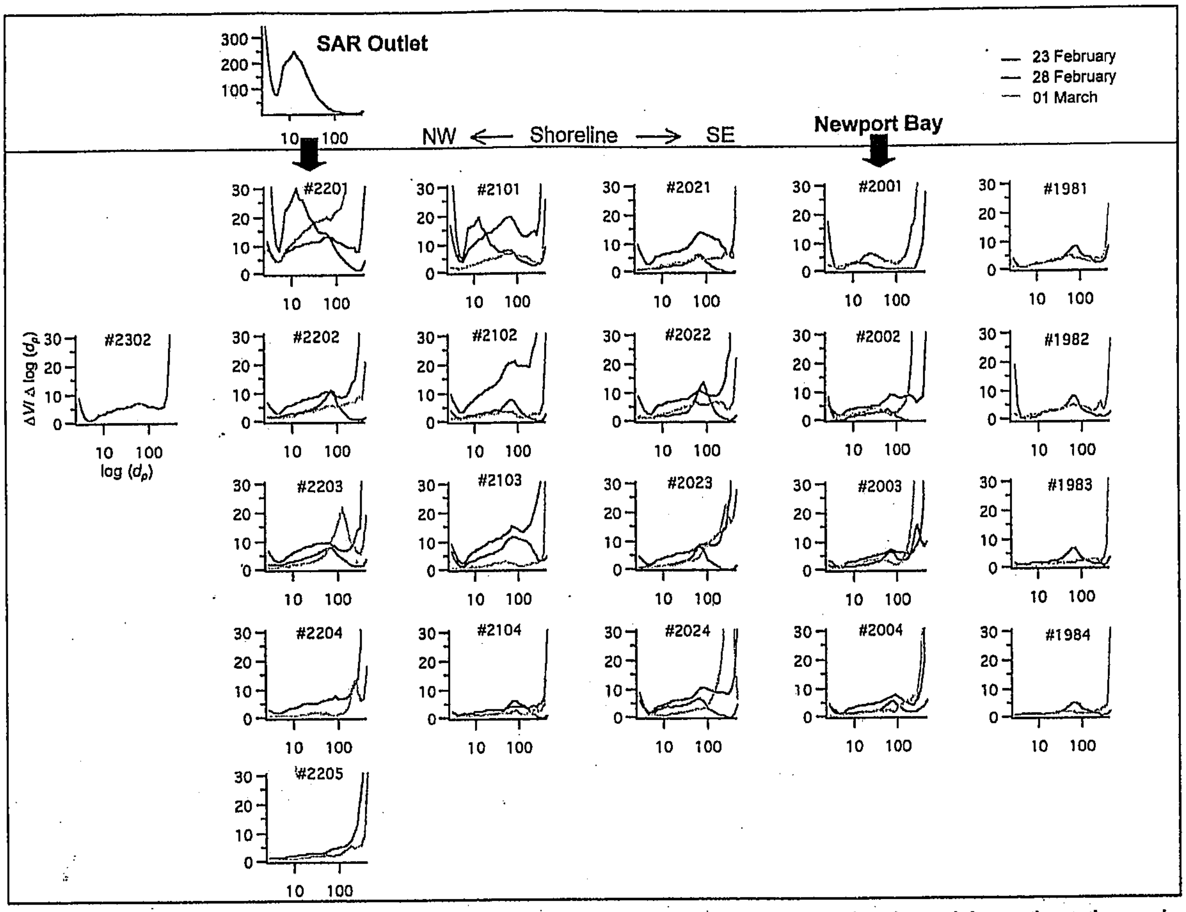

FIGURE 7. Particle size spectra measured during the three offshore cruises; numbers at the top of each panel denote the station number where the particle size spectra were measured (see Figure 1). The vertical axis in each plot represents the particle volume resident in logarithmically spaced particle diameter bins; the horizontal axis represents the diameter of the particles (in $\mu$m). These plots are arranged so that the stations progress from onshore to offshore (top to bottom) and up-coast to down-coast (left to right). The single plot labeled "SAR Outlet" corresponds to a particle size spectrum measured in stormwater runoff flowing out of the Santa Ana River outlet, just upstream of where it flows over the beach and into the ocean.

**Offshore Measurements: Particle Size Spectra.** Particle size spectra acquired during the three cruises are presented in Figure 7. Each plot displays the normalized particle volume (vertical axis) detected in 32 logarithmically spaced particle diameter bins ranging in size from 2.5 to 500 $\mu$m (horizontal axis). The particle size spectrum measured at a particular offshore location and time appear to be related to the specific stormwater plume the particles are associated with and, possibly, the elapsed time stormwater has spent in the ocean. Stormwater flowing out of the Santa Ana River during the February 23 cruise, for example, is characterized by two modes at the small end of the size spectrum, one in the <5 $\mu$m bin and another in the 10–50 $\mu$m bins (set of red curves, Figure 7). These modes are present in stormwater runoff sampled at several locations in the Santa Ana River watershed (*13*), in samples collected at the ocean outlet of the Santa Ana River (panel labeled "SAR Outlet" at top of Figure 7), and in samples collected just offshore (red curve at station 2201, Figure 7) and down-coast (red curve at station 2101, Figure 7) of the Santa Ana River outlet. Particles discharged from the Santa Ana River appear to dilute and merge into a background turbidity characterized by a single broad mode in the 50–300 $\mu$m size range (evident in the red curves at most stations, Figure 7).

Referring to Figure 3A and the earlier discussion of this satellite image, the 50–300 $\mu$m mode observed on February 23 may be characteristic of a large runoff plume originating from one or more up-coast sources of stormwater runoff, most likely the Los Angeles River or the San Gabriel River. Several factors can lead to artifacts in the particle size spectra estimated from the light-scattering instrument deployed in this study (*39*). However, in our case this caveat is mitigated somewhat by the observation that particle volume fractions calculated from the particle size spectra are strongly correlated (Spearman's rank correlation $Sp = 0.90$, $p = 0.02$) with independent measurements of total suspended solids (data not shown).

During the second and third cruises, the particle size spectra progressively coarsen with the result that, by March 1, virtually all of the particle volume is associated with the largest size bin (>500 $\mu$m, green curves in Figure 7). The observed temporal evolution in particle size spectra, from high turbidity and multiple modes at the lower end of the particle size spectrum to low turbidity and a single mode at the large end of the particle size spectrum, may reflect decreasing particle supply (i.e., reduced stormwater discharge from major river outlets) coupled with within-plume coagulation of particles into larger size classes and, ultimately, removal of the largest particles by gravitational sedimentation. Coagulation time scales estimated from these particle size spectra measurements are short (minutes to hours or longer) compared to time scales associated with the generation and offshore transport of stormwater plumes (hours to days), and hence coagulation cannot be ruled out as an important mechanism at our field site (see Supporting Information for details on the time scale calculations).



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contaminants associated with suspended particles (*13, 42*), will behave similarly.

Further offshore, stormwater runoff plumes are common and readily detected through a variety of geophysical parameters (e.g., salinity, transmissivity, surface color). A clear linkage between these parameters and fecal indicator bacteria could not be established here. However, fecal indicator bacteria did appear to be associated with the smallest particle sizes, on the basis of both fractionation studies (Figure 6B) and the inverse relationship observed between fecal indicator bacteria concentrations and number-averaged particle size (Figure 6A). Particle size spectra in the offshore plumes coarsen with time post-release, and fecal indicator bacteria concentrations steadily drop (see the schematic representation of particle size in the various offshore plumes, Figure 8B). These results have several implications. First, they suggest that high concentrations of fecal indicator bacteria in the surf zone at our field site are probably not brought into the study area by coastal currents from distal sources (e.g., the Los Angeles river or the San Gabriel river). Second, cross-shore transport of water between the surf zone and offshore of the surf zone, for example, by rip cell currents, is likely to improve surf zone water quality by diluting dirty river effluent entrained in the surf zone with relatively clean ocean water from offshore.

While the concentrations of fecal indicator bacteria in the offshore plumes are generally below surf zone water quality standards, particularly during the latter two cruises, fecal indicator viruses ($F^+$ coliphage) were detected in nearly all offshore samples tested, and human adenoviruses and enteroviruses were detected in several offshore samples, including two collected offshore of the Santa Ana River outlet (station 2201 on February 23 and 28, see Figure 5). It is likely that the virus results presented here represent a conservative estimate of viral prevalence, because a limited numbers of samples were tested ($n = 8$). In addition, the presence of PCR inhibitors in stormwater reduces the efficiency of PCR detection of human pathogenic viruses, as mentioned earlier. At present, there are no water quality standards for fecal indicator viruses and human pathogenic viruses, largely because epidemiological data are not available to link adverse human health outcomes (e.g., gastrointestinal disease) to recreational ocean exposure to these organisms. However, the offshore detection of human pathogenic viruses begs several questions: First, do these viruses constitute a human health risk, either by contaminating the surf zone directly (see arrow with question mark, indicting the possible transfer of contaminants from offshore into the surf zone, Figure 8B) or by sequestering in offshore sediments? Second, given the fact that the Santa Ana River has separate storm and sanitary sewer systems, what is the source of human fecal pathogens in the wet weather water runoff? Many studies have shown that human fecal pathogens are associated with storm runoff from urban areas located throughout the United States (*25, 43–45*), so the association between stormwater runoff and human fecal pathogens observed here is certainly not unique. Possible sources of human pathogens in stormwater runoff from urban areas include leaking sewer pipes, illicit sewage connections to the stormwater sewer system, homeless populations, and so forth.

Taken together, the results presented in this paper demonstrate that stormwater runoff from the Santa Ana River is a significant source of near-shore pollution, including turbidity, fecal indicator bacteria, fecal indicator viruses, and human pathogenic viruses. However, relationships between variables (e.g., between turbidity and fecal indicator bacteria and between fecal indicator bacteria and human viruses) vary from site to site (at the same time) and from time to time (at the same site) suggesting that the sources, fate, and transport processes are contaminant specific. The apparent exception is the inverse relationship observed between fecal indicator bacteria and number-averaged particle size, although further studies are needed to determine if this result is generalizable to other storm seasons and coastal sites and, if so, to determine the underlying mechanism at work. The relationship between water quality parameters (e.g., fecal indicator bacteria), turbidity, and other field proxies, such as number-averaged particle size, salinity, and colored dissolved organic matter, are the focus of ongoing and future regional studies, including as part of a coastal water quality observing program within the Bight '03 Project (http://www.sccwrp.org/regional/03bight/bight03_fact_sheet.html), as well as other investigations being carried out as part of the Southern California Coastal Ocean Observing System (SCCOOS).

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## Supporting Information Available

Sampling and analysis protocols, calculation of the orthokinetic coagulation time scales, and additional figures. This material is available free of charge via the Internet at http://pubs.acs.org.

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# Locating Sources of Surf Zone Pollution: A Mass Budget Analysis of Fecal Indicator Bacteria at Huntington Beach, California

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The surf zone is the unique environment where ocean meets land and a place of critical ecological, economic, and recreational importance. In the United States, this natural resource is increasingly off-limits to the public due to elevated concentrations of fecal indicator bacteria and other contaminants, the sources of which are often unknown. In this paper, we describe an approach for calculating mass budgets of pollutants in the surf zone from shoreline monitoring data. The analysis reveals that fecal indicator bacteria pollution in the surf zone at several contiguous beaches in Orange County, California, originates from well-defined locations along the shore, including the tidal outlets of the Santa Ana River and Talbert Marsh. Fecal pollution flows into the ocean from the Santa Ana River and Talbert Marsh outlets during ebb tides and from there is transported parallel to the shoreline by wave-driven surf zone currents and/or offshore tidal currents, frequently contaminating >5 km of the surf zone. The methodology developed here for locating and quantifying sources of surf zone pollution should be applicable to a wide array of contaminants and coastal settings.

## Introduction

The coastal ocean is both a critical natural resource and a final repository for all manner of human waste. The latter inexorably diminishes the former, as evidenced by a wide spectrum of coastal ills, including frequent postings and closures of popular swimming beaches (*1–3*). Coastal pollution often comes to light during the course of routine surf zone monitoring programs, in which samples are periodically collected from a series of monitoring stations and analyzed for one or more pollutants. In this paper, we demonstrate that the loading of pollutants into the surf zone (rate of input in pollutant mass per time) can be computed from a mass budget analysis of surf zone monitoring data, thereby providing critical information about the location, magnitude, and timing of specific inputs of pollution to the coastal ocean. The mass budget analysis described here is complementary to chemical and microbiological pollutant source tracking methodologies (*4*), for which the goal is typically to characterize the relative contributions of specific types of fecal pollution; for example, from human, bird, cow, etc. The approach is also complementary to other modeling approaches; for example, forward modeling of pollutant fate and transport in the ocean (*5–7*) and surf zone (*8–10*). The latter approaches rely on a *microscopic* mass balance modeling of pollutant fate and transport in which one or more differential equations are derived and solved (either exactly or numerically) subject to suitable initial and boundary conditions. In contrast, the approach described in this paper relies on a *macroscopic* mass balance, in which application of the Reynolds Transport Theorem leads to algebraic equations that can be employed to calculate the loading of pollutants in to and out of the surf zone.

The paper is organized as follows. Nearshore currents affecting the transport and mixing of pollutants in the surf zone are reviewed, followed by observations of fecal indicator bacteria pollutant transport in the surf zone at Huntington State Beach. These observations motivate the development of the mass budget analysis and its application to measurements of fecal indicator bacteria in the surf zone at Huntington State Beach. To make the results and analysis accessible to a broad audience, each section begins with a question around which the section is focused together with an answer supported by the data and modeling.

## Nearshore Currents

**Question:** *What are the dominant nearshore currents that affect the fate and transport of pollutants introduced into the surf zone?*

**Answer:** *Pollutants entrained in the surf zone are carried parallel to shore by wind and wave-driven currents and cross-shore by rip currents, vertically stratified shear flows, and offshore forced currents (e.g., internal waves). Just offshore of the surf zone, pollutants are transported by coastal currents that respond to tides, winds, and remote forcing. The combination of longshore and cross-shore advective transport enhances the longshore spreading of nearshore pollution by dispersion. The region of the surf zone impacted by coastal pollution can be influenced by the tidal phasing of pollutant input to the surf zone (e.g., from tidal outlets along the shoreline), the tidal phasing of coastal currents, and the prevailing wave climate.*

The fate and transport of pollutants in the surf zone is controlled by a set of highly dynamic currents that determine longshore transport and exchange with offshore. These can be broadly classified as *surf zone currents*, which are primarily wave-driven, and *coastal currents* offshore of the wave-driven surf zone, which are primarily driven by tides, winds, and remote forcing (Figure 1). Wave-driven surf zone currents flow parallel to the shoreline (so-called "longshore drift") in a direction controlled by the angle at which waves approach the shore. In the simple case of a straight sandy beach bordering a uniformly sloping submarine shelf, the surf zone current takes on the direction of the approaching deep-water waves (*11, 12*). At beaches bordering more complex bathymetry (e.g., with submarine headlands and canyons), refraction of the deep-water waves can generate surf zone

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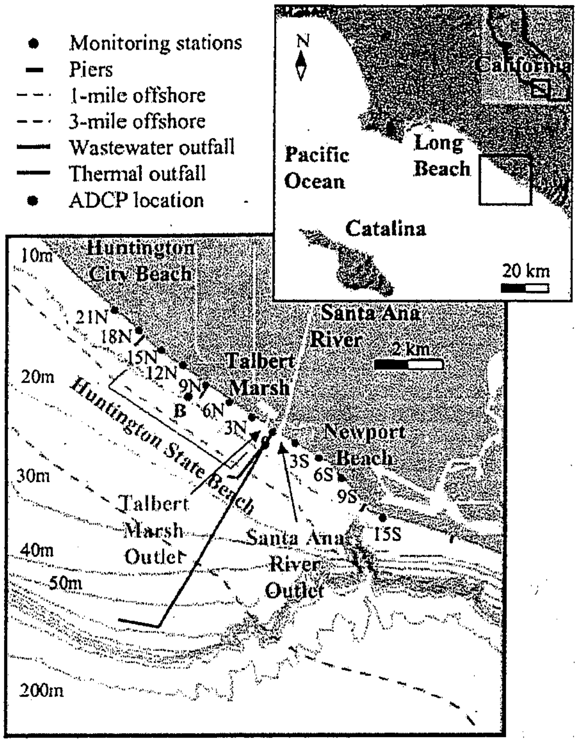


FIGURE 2. Map of the field area showing the location of surf zone monitoring stations (solid blue circles), which are designated in thousands of feet north or south of the Santa Ana River outlet; e.g., surf zone stations 15N and 15S are 15 000 ft north and south, respectively, of the Santa Ana River outlet. Also shown are several known point sources of fecal indicator bacteria including a wastewater outfall, a power plant thermal outfall, and the tidal outlets of the Santa Ana River and the Talbert Marsh (between surf zone stations 0 and 3S and 0 and 3N, respectively). The location of an Acoustic Doppler Current Profiler (ADCP) is also shown (station B, red filled circle). The map was downloaded from the U.S. Geological Survey website (http://www.usgs.gov) and modified.

*patterns can be identified. The concentration of TC is highest during the transition from the nighttime falling to rising tide and mostly confined to the region of the surf zone upcoast of the Santa Ana River and Talbert Marsh outlets. This pattern suggests that TC originates in ebb flow from the two tidal outlets and, once entrained in the surf zone, is carried upcoast by wave-driven surf zone currents and/or tidally driven coastal currents. The concentration of EC and ENT, on the other hand, is highest in a region 2 km upcoast of the Santa Ana River and Talbert Marsh tidal outlets and exhibits a more complex tidal signature. Possible explanations for the different occurrence patterns of TC, on one hand and EC and ENT on the other hand include the following: (1) The existence of multiple shoreline sources of fecal pollution, each with different relative abundance of TC, EC, and ENT and/or (2) differential fate and transport of the different fecal indicator bacteria groups in the ocean. Although these two occurrence patterns appear to be reproducible, there is significant study-to-study variability, and the data were acquired over a limited number of environmental conditions (e.g., all studies were conducted during spring tides and during summer dry weather). Hence, additional occurrence patterns cannot be ruled out based on the existing data.*

**Description of Field Site.** In this study, we investigated surf zone pollution at a set of contiguous beaches (including Newport Beach, Huntington State Beach, and Huntington City Beach, see Figure 2) located along a NW–SE striking section of the Pacific coastline, between Los Angeles and San Diego, in Orange County, California. Several areas of Huntington State Beach have suffered chronic beach postings and closures over the past several years due to elevated concentrations of fecal indicator bacteria in the surf zone (*20*). This beach is also very popular (more than 5 million visitors per year), and the combination of surf zone pollution and significant beach usage implies that a large number of people (perhaps as many as 50 000) may acquire highly credible gastroenteritis from swimming and surfing in this area each year (*21*). It appears that the fecal indicator bacteria pollution at Huntington State Beach originates from a combination of sources, including bird droppings deposited in the Talbert Marsh, regrowth of bacteria on vegetation and marsh sediments, and dry and wet weather runoff from the surrounding community (*22, 23*). Additional *potential* sources of fecal indicator bacteria include the offshore discharge of partially treated sewage effluent (*24*), the offshore discharge of power plant cooling water that contains fecal indicator bacteria from plant wash-down and other activities (*25*), bather shedding (*26*), the accumulation of bird droppings along the shoreline and offshore (*27*), the exfiltration of sewage-contaminated groundwater (*28*), and contributions from watershed outlets located north and south of the study area including the Los Angeles River, the San Gabriel River, and outlets for Huntington Harbor and Newport Bay (*29*). The thermal boil generated by the power plant cooling water discharge also provides a potential mechanism for transporting contaminants from offshore into the surf zone, as documented in a separate study (*28*). Several of these potential sources of fecal indicator bacteria pollution (including the wastewater treatment outfall and the power plant cooling water outfall) are noted on the map in Figure 2.

**Methods.** To better constrain sources of fecal pollution in the surf zone at our study site, four separate field experiments were carried out during the summer of 2001. During each experiment, water samples were collected every hour for 48 consecutive hours from 11 different surf zone monitoring stations (528 samples per study for a total of 2132 samples). The locations of the surf zone monitoring stations are indicated on the map in Figure 2 (blue circles). In this figure, the stations are designated according to their distance (in thousands of feet) north or south of the Santa Ana River outlet (e.g., 15 N is located approximately 15 000 ft, approximately 5 km, north of the Santa Ana River outlet). Each station was manned by a separate team of samplers who collected the surf zone samples (100 mL total volume) every hour from ankle-depth water on an incoming wave. The water samples were immediately placed on ice and transported to the Orange County Sanitation District laboratory (Fountain Valley, CA) where they were analyzed within 6 h of collection for total coliform (TC), *E. coli* (EC, a subset of fecal coliform), and *Enterococci* bacteria (ENT) using defined substrate tests known commercially as Colilert-18 and Enterolert (IDEXX, Westbrook, MN) implemented in a 97-well quanti-tray format. The four studies were carried out on the following dates in 2001: June 19–21, July 5–7, July 19–21, and August 19–21. The timing of the studies coincided with spring tides, when surf zone water quality at Huntington State Beach is frequently impaired (*30*); all studies were conducted during dry weather periods. Additional special surf zone studies were conducted during the summer of 2001, as described elsewhere (*28*). These additional studies are not included here because of their relatively short duration (<24 h).

**Results and Discussion.** The color contour plots in Figure 3 depict the concentration of fecal indicator bacteria measured at different stations and times during the four surf zone studies. In these plots, the color ranges from blue for fecal indicator bacteria concentrations falling below the lower limit of detection (<10 most probable number (MPN)/100 *add'a'* and *bcc'b'* by wave-driven surf zone currents and turbulent mixing; (2) face *abb'a'* by, for example, tidal exchange at an estuary outlet; (3) face *dcc'd'* by cross-shore currents and turbulent mixing; (4) face *a'b'c'd'* by exchange with the sediment bed; and (5) face *abcd* by exchange with the atmosphere.

Conservation of mass requires that accumulation of pollutant mass inside the surf zone prism must equal the net flux of pollutants across all boundaries of the surf zone prism plus any loss of pollutant inside the surf zone prism by reaction, as expressed quantitatively through the Reynolds Transport Theorem (*36*):

$$\frac{\partial}{\partial t}\int_V C(\mathbf{x},t)\,\mathrm{d}V = -\int_A \mathbf{q}(\mathbf{x},t)\cdot\mathbf{n}\,\mathrm{d}A - \int_V R(\mathbf{x},t)\,\mathrm{d}V \quad (1)$$

The variables in eq 1 represent time ($t$), spatial coordinate ($\mathbf{x}$), pollutant concentration ($C(\mathbf{x},t)$, units of mass per volume), pollutant flux vector ($\mathbf{q}$, units of mass per area per time), pollutant reaction rate ($R(\mathbf{x},t)$, units of mass per volume per time), and the outward facing unit vector oriented normal to the surface of the surf zone prism ($\mathbf{n}$, unitless). The integrals in eq 1 are evaluated over the volume ($V$) or surface area ($A$) of the surf zone prism.

The flux of pollutants across the surface of the surf zone prism (first term on the right-hand side, RHS, of eq 1) can be divided into three parts: the part that crosses face *add'a'*, the part that crosses face *bcc'b'*, and the part $S(t)$ crossing all other faces (i.e., pollutant pathways 2–5 above):

$$-\int_A \mathbf{q}(\mathbf{x},t)\cdot\mathbf{n}\,\mathrm{d}A = \int_{add'a'} q_y(\mathbf{x},t)\,\mathrm{d}A - \int_{bcc'b'} q_y(\mathbf{x},t)\,\mathrm{d}A + S(t) \quad (2)$$

where $q_y$ represents the component of the pollutant flux oriented parallel to the shoreline. *The magnitude and sign of the variable S(t) provides critical information about the nature of contaminant loading into the surf zone prism from onshore and offshore sources of pollution.* Specifically, $S(t)$ is positive if the rate of pollutant addition by pathways 2–5 exceeds loss by rip current export or other processes; conversely, $S(t)$ is negative if pollutant loss exceeds input from pathways 2–5.

Combining eqs 1 and 2 and solving for $S(t)$, we arrive at the following expression for pollutant loading into the surf zone in terms of flux across boundaries *add'a'* and *bcc'b'* (first and second terms on RHS) and accumulation and reaction of pollutant in the surf zone prism (third and fourth terms on RHS):

$$S(t) = \int_{bcc'b'} q_y(\mathbf{x},t)\,\mathrm{d}A - \int_{add'a'} q_y(\mathbf{x},t)\,\mathrm{d}A + \frac{\partial}{\partial t}\int_V C(\mathbf{x},t)\,\mathrm{d}V + \int_V R(\mathbf{x},t)\,\mathrm{d}V \quad (3)$$

Apart from the conceptualization of surf zone transport illustrated schematically in Figure 1, no significant approximations have been employed in deriving eq 3. However, to estimate the magnitude of terms appearing on the RHS side of this last equation will require, in practice, assumptions regarding the mathematical formulation of each term. Clearly, a tradeoff exists between how well the transport processes at a particular site are characterized by field measurements and the number and nature of assumptions required to translate the field measurements into estimates for the magnitude of terms on the RHS of eq 3. In our case, we employed a set of physically reasonable assumptions that yield estimates for the terms on the RHS of eq 3 based only on hourly measurements of fecal indicator bacteria concentration $C(y,t)$ in the surf zone at two adjacent shoreline station (located at $y = 0$ and $L$) together with an estimate for the longshore surf zone current (averaged over the cross section *add'a'* and *bcc'b'*)$\langle v_y\rangle$, the fecal indicator bacteria die-off rate constant $k_{FIB}$, and hourly measurements of sunlight intensity $I(t)$. The result is the following approximate expression for pollutant loading (see Supporting Information):

$$S(t) \approx \frac{Lwh}{2}\left[\frac{1}{2\Delta t}(C(0,t+\Delta t) + C(L,t+\Delta t) - C(0,t) - C(L,t)) + \frac{\langle v_y\rangle(C(L,t) - C(0,t))}{L} + k_{\mathrm{FIB}}I(t)\frac{C(0,t) + C(L,t)}{2}\right] \quad (4)$$

where $L$, $w$, and $h$ represent the length, width, and time-averaged water depth at the ocean-ward edge of the surf zone prism (see Figure 1), and $\Delta t$ represents the time interval between fecal indicator bacteria concentration measurements. As detailed in the Supporting Information, eq 4 is only valid in cases where the pollutant flux across faces *add'a'* and *bcc'b'* is dominated by longshore advection. A more complex expression is included in the Supporting Information for cases when both advection and turbulent diffusion contribute to the longshore flux of pollutants. For the range of die-off rates utilized and solar insolation values measured, the $T_{90}$ (i.e., time for 90% die-off) range from no die-off (at night when $I(t) = 0$) to 1.3, 1.4, and 2.4 h (for TC, EC, and ENT, respectively) when the insolation values are maximal ($I(t) = 1000$ W m$^{-2}$).

It is important to consider how estimates of the loading rate (i.e., the magnitude and sign of $S(t)$) will be affected by uncertainty in the magnitude of variables that appear on the RHS of eq 4. The variance in $S(t)$ (denoted here as $u(S)$) can be related to the variance of any variable $X_i$ (denoted $u(X_i)$) appearing on the RHS of eq 4 through the *Law of Propagation of Uncertainty* (*37*), also known as a *First-Order Uncertainty Analysis* (*38–40*):

$$u^2(S) = \sum_{i=1}^{N} u^2(X_i)\left[\frac{\partial S}{\partial X_i}\right]^2 + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N} u(X_i)\,u(X_j)\,r(X_i,X_j)\left[\frac{\partial S}{\partial X_i}\right]\left[\frac{\partial S}{\partial X_j}\right] \quad (5)$$

where $X_i$ represents the set of $N = 10$ variables $\{L, w, \Delta t, \langle v_y\rangle, k_{FIB}, I, C(0,t), C(L,t), C(0,t+\Delta t), C(L,t+\Delta t)\}$ and $r(X_i,X_j)$ represents the correlation coefficient for any two variables $X_i$ and $X_j$. The variance associated with each variable $X_i$ was estimated as follows:

$$u(X_i) = U_R(X_i)\,|X_i| \quad (6)$$

where $U_R(X_i)$ represents the relative variance of the variable $X_i$ and $|X_i|$ represents the magnitude of the variable in question (which may vary with time) (*41*). The relative variances $U_R(X_i)$

**TABLE 1. Relative Uncertainties of Variables Used To Estimate Fecal Indicator Bacteria Loading Rates**

| quantity, $X_i$ | relative uncertainty, $U_R(X_i)$ | evaluation of uncertainty by |
|---|---|---|
| $I$ | 0.05 | manufacturer's specification |
| $C$ | 0.05 | manufacturer's specification |
| $k_{FIB}$ | 0.10 | ref *42* |
| $L$ | 0.05 | personal communication |
| $w$ | 0.10 | scientific judgment |
| $\Delta t$ | 0.10 | personal communication |
| $\langle v_y\rangle$ | 0.10 | scientific judgment |



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were estimated from manufacturers specifications (for the variables $I$ and $C$), previously published estimates (for the variable $k_{FIB}$) (42), and scientific judgment or personal communication (for the variables $L$, $w$, $\Delta t$, and $\langle v_y \rangle$) (37) (see Table 1). Application of eqs 4 and 5 to surf zone monitoring data yields estimates for the magnitude, sign, and variance of the loading of pollutants in to or out of a given region of the surf zone. For practical purposes, we assumed that any loading estimate with a relative variance of $U_R(S) < 0.317$ was meaningful; this choice of relative variance is equivalent to saying that, within a confidence level of 68% (one standard deviation), the true value of the loading lies within the range $S \pm 0.317|S|$ (37).

## Test of the Surf Zone Mass Budget Analysis

**Question:** *Can the loading rate equation derived in the last section accurately predict the loading of fecal pollution into the surf zone from specific shoreline sources?*

**Answer:** *Loading rates estimated from eq 4 closely track direct measurements of the loading of TC, EC, and ENT into the surf zone from the Talbert Marsh outlet and the loading of TC from the Santa Ana River outlet. The comparison is not favorable for the loading of EC and ENT from the Santa Ana River outlet, perhaps because there were other sources (i.e., other than the Santa Ana River) for the last two fecal indicator bacteria groups during this particular field experiment.*

As a first test of our methodology for calculating pollutant budgets for the surf zone, we compared fecal indicator bacteria loading rates calculated from surf zone monitoring data (eq 4) with independent estimates of the load of fecal indicator bacteria flowing into the surf zone from the Santa Ana River and Talbert Marsh outlets (eq 7):

$$S_{\text{outlet}}(t) = C_{\text{outlet}}(t)\, Q_{\text{outlet}}(t) \qquad (7)$$

In this last equation, $S_{\text{outlet}}(t)$ represents the loading (in bacteria per time) flowing into the surf zone from either the Santa Ana River and Talbert Marsh outlets during ebb tides ($S > 0$) or flowing into the outlets from the surf zone during flood tides ($S < 0$) (the flow at the Santa Ana River and Talbert Marsh outlets is tidally forced during dry weather periods). The variables $C_{\text{outlet}}(t)$ and $Q_{\text{outlet}}(t)$ represent hourly measurements of the fecal indicator bacteria concentration and volumetric flow rate, respectively, at the Santa Ana River or Talbert Marsh outlets. Details of how these variables were estimated can be found in the Supporting Information. Direct comparison of loading rates estimated from eqs 4 and 7 was only possible during the second surf zone study (July 5–7, 2001) because this was the only study when hourly measurements were available for the concentration of fecal indicator bacteria at all surf zone stations and in the outlets of the Santa Ana River and Talbert Marsh. In addition, estimates for the volumetric flow rate (i.e., $Q_{\text{outlet}}(t)$) of water flowing in to and out of the Santa Ana River and Talbert Marsh outlets were measured only during this single study.

TC loading rates estimated from the surf zone monitoring data generally agree with independent measurements of TC flowing into the surf zone from the two watershed outlets (compare dashed and solid lines in the TC graphs in panels B and C, Figure 4). TC loading rates peak around 0.5–1 trillion MPN/h during falling tides when water from the Talbert Marsh and Santa Ana River outlets flows into the ocean (compare loading rates with tide level curves in panel A); in some cases, the loading of TC from the Santa Ana River extends into the next flood tide because the change in flow direction at the outlets (from ebb to flood) sometimes lags the change from falling to rising tide (compare velocity measurement at the outlet of the Santa Ana River in panel B to water level curves in panel A). It is noteworthy that the loading of TC into the surf zone from the two outlets often peak *at the end of the ebb tide* or slightly into the next flood tide, when the coastal current is often switching to an upcoast direction (see Figure S1). The observation that peak pollutant input from the Santa Ana River and Talbert Marsh outlets immediately precedes upcoast-directed coastal currents may explain why much of the TC pollution appears in the surf zone upcoast of the Santa Ana River and Talbert Marsh outlets, even during periods of weak westerly waves when the surf zone current might be directed downcoast (see discussion of TC occurrence patterns). In any case, the results presented in Figure 4 are consistent with the idea that TC loading in the surf zone between stations 3S and 3N is dominated by ebb flow from the Santa Ana River and Talbert Marsh outlets. Furthermore, the comparability of the two loading estimates (i.e., from eqs 4 and 7) lends credibility to the methodology described here for calculating pollutant loadings from surf zone monitoring data (i.e., eq 4).

The loading of EC and ENT calculated from the Talbert Marsh outlet data (eq 7) also agrees fairly well with the loading of EC and ENT calculated from the surf zone monitoring data at stations 0 and 3N (eq 4), particularly during the second large ebb event (panel C in Figure 4). However, the loading of EC and ENT calculated from the Santa Ana River outlet data does not correlate with EC and ENT loading calculated from the surf zone monitoring data at stations 3S and 0 (panel B in Figure 4). Indeed, on at least two occasions, ENT loading calculated from eq 7 is negative ($S < 0$) while the ENT loading calculated from eq 4 is positive ($S > 0$), suggesting that ENT was flowing into the surf zone from some other (i.e., not Santa Ana River) source. Other potential sources of surf zone pollution are explored in the next section.

## Shoreline Sources and Tidal Phasing of Fecal Bacteria Loading

**Question:** *Can the loading equation (eq 4) derived in this study be used to identify the location and tidal phasing of sources of fecal indicator bacteria in the surf zone?*

**Answer:** *When applied to fecal bacteria monitoring data collected during the first two studies (June 19–21 and July 5–7, 2001), the loading equation indicates that TC loading in the surf zone is greatest around the mouths of the Santa Ana River and Talbert Marsh outlets and flows into the surf zone primarily during the nighttime falling tides. While these outlets also contribute EC and ENT, a larger source of these latter fecal indicator bacteria groups is located approximately 2 km upcoast of the outlets, around surf zone stations 6N–9N. This last observation is consistent with an earlier sanitary survey, which implicated subsurface sewage collection pipes as a source of sewage contamination in the surf zone around surf zone station 6N–9N.*

As a next step in our analysis, we used the loading equation derived in the last section (eq 4) to estimate the loading of fecal indicator bacteria into a 10-km stretch of the surf zone (from 15S to 21N surf zone stations) centered around the Santa Ana River and Talbert Marsh outlets. The loading estimates were calculated from measurements of fecal indicator bacteria in the surf zone (as described earlier) together with estimates for specific parameters (e.g., longshore drift velocity) as described in the Supporting Information for this paper. Of the four surf zone studies conducted, only the first two (*June 19–21 and July 5–7, 2001*) coincided with wave conditions (i.e., southerly swells) that were likely to yield upcoast-directed longshore drift in the surf zone. Furthermore, during these first two studies, TC originating from the Santa Ana River and Talbert Marsh outlets appears to be transported in an upcoast direction at a fairly constant rate (implied longshore drift of approximately 0.3 m/s, see black lines in the two upper left panels in Figure 3). Indeed, the tilt of the TC events can be used to estimate the longshore



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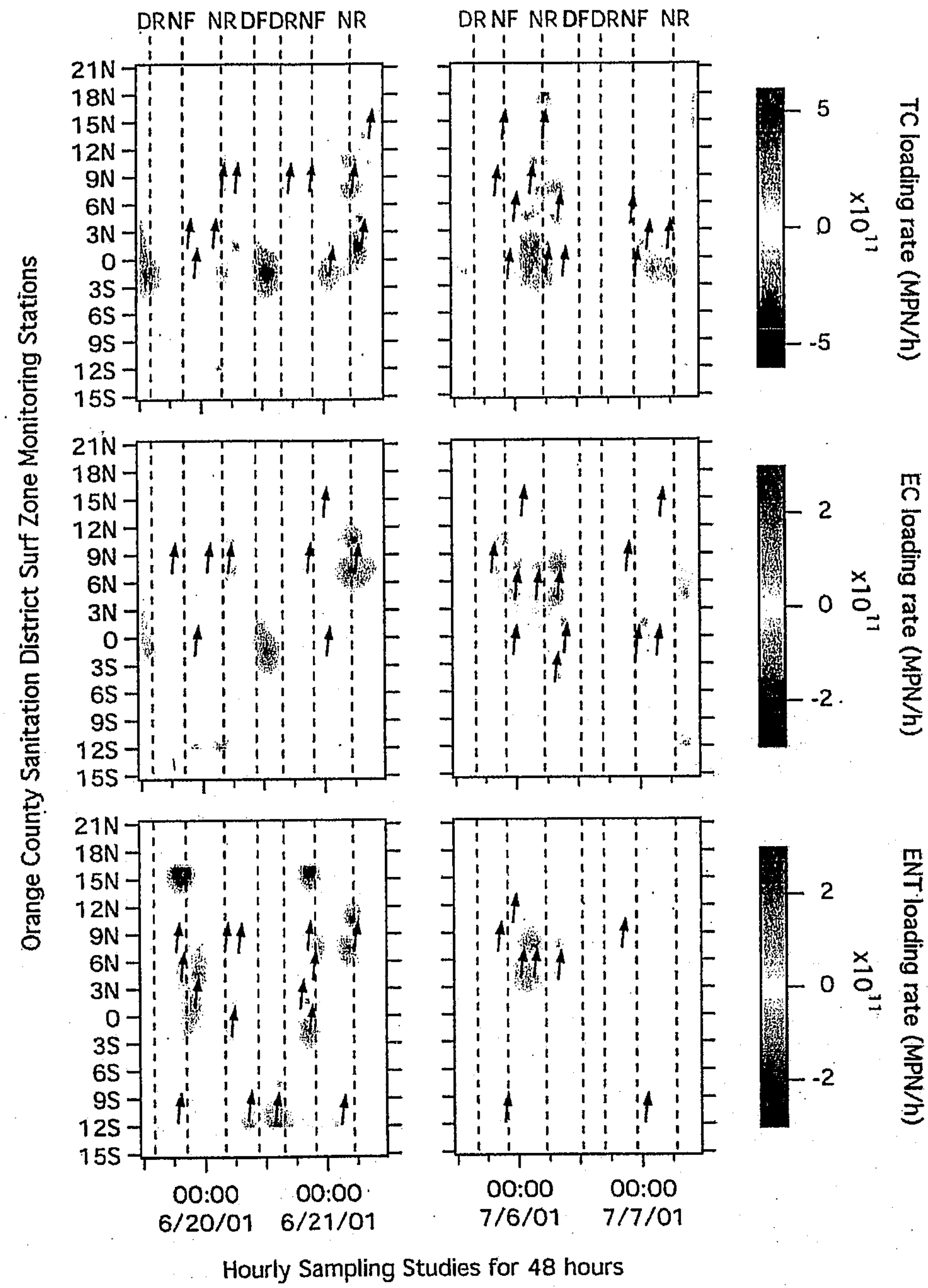


**FIGURE 5. Spatial distribution of fecal indicator bacteria loads calculated from hourly surf zone monitoring data on two separate occasions (both 2001): June 19–21 and July 5–7. Regions of the surf zone that are a net source of fecal indicator bacteria appear red ($S > 0$), and regions that are a net sink of fecal indicator bacteria (e.g., by rip current export) appear blue ($S < 0$). Arrows indicate source/removal pairs for which the loading estimates had relative uncertainties $U_R(S) < 0.317$. The orientation of the arrow represents the long-shore drift velocity $\langle v_y \rangle$ estimated from the tilt of the TC events (see Figure 3). The abbreviations DR, NF, NR, and DF correspond to the beginning of daytime rising, nighttime falling, nighttime rising, and daytime falling tides, respectively.**

associated with the wave-driven surf zone current (i.e., the source/removal pairs are oriented parallel to the arrows). Our interpretation of these source/removal patterns is that fecal indicator bacteria enter the surf zone at relatively well-defined locations along the shore (over shoreline distances of <2 km) and from there are transported upcoast by wave-driven surf zone currents and removed from the surf zone by cross-shore currents or other (nondie-off) processes, such as coagulation and sedimentation.

Referring to the spatial distribution of red color in the top two panels in Figure 5, the largest and most consistent sources of TC are located in the region of the surf zone between 3S and 3N where the Santa Ana River and Talbert Marsh outlets discharge into the ocean (peak loading of about 1 trillion MPN/h). Relatively weaker sources of TC occur sporadically north of the Santa Ana River and Talbert Marsh outlets, from about 3N to 15N. Virtually no sources of TC are noted south of the Santa Ana River. Sources of EC and ENT occur at the outlet of the Santa Ana River (between surf zone stations 3S and 0), upcoast around surf zone stations 6N–9N (peak loading of about 0.7 trillion MPN/h), and for ENT occasionally in the southern portion of the field area around 12S (peak loading of 0.4 trillion MPN/h). During the first field study, two large ENT events (peak loading of 1.2 and 1.7 trillion

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# Surf zone entrainment, along-shore transport, and human health implications of pollution from tidal outlets

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[1] Field experiments and modeling studies were carried out to characterize the surf zone entrainment and along-shore transport of pollution from two tidal outlets that drain into Huntington Beach and Newport Beach, popular public beaches in southern California. The surf zone entrainment and near-shore transport of pollutants from these tidal outlets appears to be controlled by prevailing wave conditions and coastal currents; and fine-scale features of the flow field around the outlets. An analysis of data from dye experiments and fecal indicator bacteria monitoring studies reveals that the along-shore flux of surf zone water is at least 50 to 300 times larger than the cross-shore flux of surf zone water. As a result, pollutants entrained in the surf zone hug the shore, where they travel significant distances parallel to the beach before diluting to extinction. Under the assumption that all surf zone pollution at Huntington Beach originates from two tidal outlets, the Santa Ana River and Talbert Marsh outlets, models of mass and momentum transport in the surf zone approximately capture the observed tidal phasing and magnitude of certain fecal indicator bacteria groups (total coliform) but not others (*Escherichia coli* and enterococci), implying the existence of multiple sources of, and/or multiple transport pathways for, fecal pollution at this site. The intersection of human recreation and near-shore pollution pathways implies that, from a human health perspective, special care should be taken to reduce the discharge of harmful pollutants from land-side sources of surface water runoff, such as tidal outlets and storm drains.

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## 1. Introduction

[2] Oceans adjacent to large urban communities, or "urban oceans," are the final repositories of human waste from a myriad of sources [*Culliton*, 1998]. Historically, pollutant loading to the urban ocean was dominated by point sources of untreated or partially treated sewage [e.g., *Murray et al.*, 2002]. Improvements in sewage treatment and disposal technology, together with better source controls, have progressed to the point that, nowadays, pollutant loading rates to the urban ocean are often dominated by non-point sources of pollution, typically in the form of dry and wet weather surface water runoff [*Schiff et al.*, 2000]. Unlike sewage, which is typically discharged far offshore through long submarine outfalls [*Koh and Brooks*, 1975], runoff flows into the ocean at the surfline where dilution is minimal and the likelihood of human contact is greatest [*Inman and Brush*, 1973]. In southern California, contamination of the surf zone by dry weather runoff apparently increases the risk that marine recreational bathers will contract diarrhea and other acute illnesses [*Haile et al.*, 1999; *Dwight et al.*, 2004]. In turn, illnesses caused by recreating in contaminated ocean waters have annual economic impacts ranging into the millions of dollars locally [*Dwight et al.*, 2005] and into the billions of dollars globally [*Shuval*, 2003]. Dry and wet weather runoff from urban areas contains both human viruses [*Jiang and Chu*, 2004; *Ahn et al.*, 2005; *Jiang et al.*, 2001; C. Surbeck et al., Transport of suspended particles and fecal pollution in storm water runoff from an urban watershed in southern California, submitted to *Environmental Science and Technology*, 2005] and elevated concentrations of fecal indicator bacteria, the organisms tested for in most marine bathing water quality monitoring programs [*Reeves et al.*, 2004]. Consequently, surface water runoff is a leading cause of beach health advisories and beach closures [*Boehm et al.*, 2002a; *Dwight et al.*, 2002; *Kim and Grant*, 2004; *Kim et al.*, 2004].

[3] The focus of this paper is the dry weather contamination of shoreline bathing waters with fecal indicator

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activities upstream of the tidal prism capture virtually all flow in the SAR during dry weather periods, and hence all low-salinity water flowing into the tidal prisms in the SAR and TM outlets is from local sources of nuisance runoff, as noted earlier. The situation changes markedly during storms, when substantial volumes of storm water runoff from the Santa Ana River watershed can flow into the ocean from the SAR outlet, contributing fecal indicator bacteria, human pathogenic and bacterial viruses, and suspended particles to the surf zone and offshore [*Ahn et al.*, 2005].

[8] A detailed description of the Huntington Beach field site–including temporal and spatial patterns of fecal contamination in the surf zone, possible sources of this pollution, and the dynamics of tidal flow in the channels that drain to Huntington Beach–can be found elsewhere [*Grant et al.*, 2001; *Boehm et al.*, 2002a, 2002b, 2004a, 2004b; *Sanders et al.*, 2001; *Kim et al.*, 2004; *Reeves et al.*, 2004; *Kim and Grant*, 2004; *Noble and Xu*, 2004; L. Rosenfeld et al., Temporal and spatial variability of fecal indicator bacteria in the surf zone off Huntington Beach, CA, submitted to *Marine Environmental Research*, 2005 (hereinafter referred to as Rosenfeld et al., submitted manuscript, 2005)]. Studies of the generation and near-shore transport of storm water runoff plumes from river outlets in southern California, including the SAR, can also be found in the literature [*Washburn et al.*, 2003; *Jones et al.*, 2002; *Warrick et al.*, 2004; *Ahn et al.*, 2005].

## 3. Field Studies

### 3.1. Materials and Methods

#### 3.1.1. Dye Studies

[9] Dye experiments were conducted during two dry weather periods in May 2000 to characterize the entrainment and along-shore transport of contaminants from the TM and SAR outlets. Rhodamine WT dye (Keystone, Santa Fe Springs, CA) was injected into the outlets of the TM and the SAR during two separate ebb tides, one on 1 May and another on 10 May 2000. The study on 1 May coincided with a spring tide when the tidal range was large (2.0 m); the study on 10 May coincided with a neap tide when the tide range was small (1.2 m). Rhodamine WT was chosen because it is relatively non-adsorbing and stable in ambient light [*Smart and Laidlaw*, 1977]. During the first experiment on 1 May, separate injections were carried out first in the TM outlet (1125–1155 PDT) and then in the SAR outlet (1245–1315 PDT). 20% (w/v) Rhodamine WT dye was pumped at a rate of $4.2 \times 10^{-5}$ m$^3$/s for approximately 30 minutes through a 5-meter PVC diffuser suspended in the middle of the channel. The evolution of the dye fields was followed over time using: 1. An airborne Digital Multi-Spectral Video sensor (DMSV Mk1 system, SpecTerra Systems, Nedlands, Australia) flown at approximately 1500 m. 2. Measurements of dye concentration in grab samples collected at stations 3N (N33°38.02′ W117°58.03′) and 9N (N33°38.57′ W117°58.92′). The locations of the SAR and TM outlets, relative to surf zone stations 3N and 9N, are indicated in Figure 1. The concentration of Rhodamine WT in the grab samples was measured with a Turner Designs 10–005 fluorometer (Turner Designs, Inc, Sunnyvale, CA) that was calibrated with the Rhodamine WT stock that was used in the experiment. The fluorometer was equipped with the Rhodamine WT filter set with excitation at 546 nm and emission at 570 nm. The injection protocol was repeated nine days later on 10 May 2000 when dye was released from the TM outlet (0810–0840 PDT) and the SAR outlet (0915–0945 PDT) during a single ebb tide.

#### 3.1.2. Fecal Indicator Bacteria Studies

[10] Water samples were collected hourly for 48 hours during a dry weather period from noon on 5 July to noon on 7 July (2001) by two different research teams—one from the University of California at Irvine (UCI) and another from the Orange County Sanitation District (OCSD)—at the following locations: 1. The UCI team collected water samples from the TM outlet, approximately 200 m upstream of where water from the marsh flows over the beach and into the ocean (station W3, Figure 1). 2. The UCI team collected water samples from two stations in the SAR outlet approximately 200 m upstream of where water from the river flows over the beach and into the ocean (stations W1 and W2, Figure 1). 3. The OCSD team collected water samples at ten surf zone stations located up-coast (north-west) and down-coast (south-east) of the SAR and TM outlets (stations 15S, 9S, 3S, 0, 3N, 6N, 9N, 12N, 15N, 21N, Figure 1; note station 21N is off of the map). The surf zone stations are designated by OCSD according to their distance (in feet) north or south of the SAR outlet; e.g., stations 6N and 9S are located 6000 feet up-coast and 9000 feet down-coast of the SAR outlet. To characterize spatial variability in the concentration of fecal indicator bacteria across the SAR outlet (i.e., transverse to the direction of tidal flow), the UCI team collected separate samples from the top and bottom of the water column at the up-coast (station W1) and down-coast (station W2) sides of the river outlet (i.e., four samples were collected from the cross-section of the SAR outlet every hour). Details of the TM and SAR outlet sampling can be found in *Grant et al.* [2002]; details of the surf zone sampling can be found in *Noble and Xu* [2004]. In brief, water samples were immediately placed on ice, and transported to OCSD (surf zone samples) or UCI (SAR and TM outlet samples) where they were analyzed for TC, EC and ENT using defined substrate tests known commercially as Colilert and Enterolert, implemented in a 96 well quantitray format (IDEXX, Westbrook, MN).

### 3.2. Results

#### 3.2.1. Dye Experiments

##### 3.2.1.1. Areal Observations of Dye Fields

[11] Environmental conditions during the four dye experiments, together with inferred along-shore mixing parameters (described below), are summarized in Table 1. Areal images of the dye fields reveal three distinct near-shore transport processes (Figure 1). Process 1: As dye-labeled water from the tidal outlets flowed over the beach and into the ocean during ebb tides, a portion was carried directly offshore in a momentum jet formed by ebb flow from the outlet, and the rest was entrained in the surf zone. Process 2: The portion of dye-labeled water entrained in the surf zone was transported parallel to the shore by wave-driven surf zone currents (referred to below as along-shore advection) and transported seaward by cross-shore currents (e.g., rip and undertow currents). Process 3: The portion of dye-labeled water taken seaward by cross-shore currents dis-

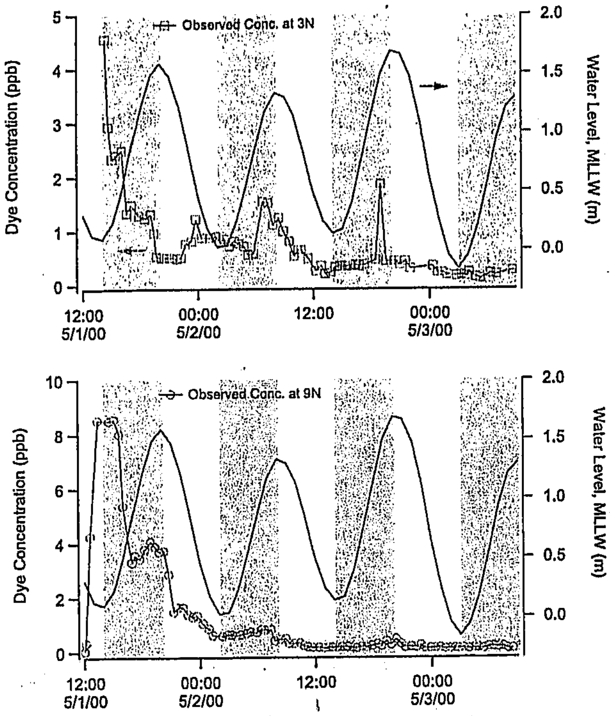


**Figure 2.** Dye concentration (red lines and markers) measured in the surf zone at (top) 3N and (bottom) 9N. Blue curves indicate the measured Mean Lower Low Water (MLLW) level. Vertical blue stripes indicate periods of rising tide.

currents, and fine-scale features of the flow field around the two outlets.

#### 3.2.1.2. In Situ Observations of Dye Fields

[17] Figure 2 presents measurements of dye concentration in the surf zone at stations 3N (top panel) and 9N (bottom panel) during and following the TM and SAR dye injections on 1 May 2000. The following temporal patterns are evident at both stations: 1. A single large dye pulse appears early in the time series (referred to here as the "primary pulse"). 2. A sequence of smaller pulses, many of which coincide with flood tides, appear later in the time series (referred to here as "secondary pulses"). Sampling at surf zone station 3N did not commence early enough to capture the leading edge of the primary pulse, but the trailing edge of the primary pulse is well defined at this station (top panel in Figure 2). The leading and trailing edges of the primary pulse are well defined at 9N; however, dye measurements saturated at a concentration of 8.5 ppb and hence the peak concentration of the primary pulse at 9N is not known.

[18] In the last section we noted that most of the dye-labeled water from the SAR outlet was ejected offshore in a momentum jet on 1 May. Hence, the primary dye pulse detected at 3N and 9N probably corresponds to the up-coast advection of dye-labeled water originating from the TM outlet. This conclusion is supported by the arrival time of the primary pulse at 9N. Under the assumption that the primary pulse originated from the TM dye injection, the arrival time of the primary pulse at 9N implies an up-coast transport velocity of 0.3 m/s, which is equal to the along-shore transport velocity of dye-labeled surf zone water independently estimated from the areal images (see last section).

[19] In considering the origin of the secondary pulses, it is important to keep in mind that dye measurements were carried out on water samples collected from ankle depth in the surf zone; in other words, the sampling points at 3N and 9N migrated up and down the beach face with the rise and fall of the tides. With this point in mind, at least two hypotheses can be formulated to explain the origin of the secondary pulses. Hypothesis 1: it takes several flood/ebb cycles to completely flush out to the ocean dye injected into the TM and SAR outlets, and hence the secondary pulses reflect the up-coast transport of dye-labeled water from the TM and/or SAR outlets released over multiple consecutive ebb tides. Hypothesis 2: the secondary pulses arise from the recycling back into the surf zone of dye that was initially ejected seaward by rip currents and/or outlet momentum jets.

[20] Multiple lines of evidence favor the second, over the first, hypothesis. First, assuming an along-shore transport velocity of 0.3 m/s it would take <1 h for effluent ejected from the TM and SAR outlets during ebb tides to reach surf zone station 3N. However, a comparison of the blue and red curves in Figure 2 (top panel) reveal that all but one of the secondary pulses at 3N peak during flood tides, between 3 to 5 h after the end of the ebb tide. Second, dye-labeled water is not evident on the areal images (Figure 1a) in the inland portions of the SAR and TM outlets during and shortly after the dye injection event. These two observations —that the tidal phasing of the secondary pulses is inconsistent with their being released from the TM and/or SAR outlets over multiple ebb events, and that areal images fail to demonstrate significant concentrations of dye left in the TM and SAR outlets post initial release–appear to rule out Hypothesis 1.

[21] The second hypothesis is consistent with areal images of the dye field that show dye-labeled water lingering just seaward of the surf zone for at least 24 h after the dye was released on 1 May (data not shown). Presumably, dye-labeled water just offshore of the surf zone could mix back into the surf zone by rip-current driven circulation cells. Over this stretch of beach, the exchange of water between the surf zone and offshore is influenced by a thermal boil generated by the submarine discharge of waste heat from a local power plant seaward of surf zone station 9N [*KOMEX $H_2O$ Science Incorporated*, 2003]. The observation that the secondary pulses occur during flood tides may result from the interaction between this thermal boil (which apparently enhances cross-shore transport) and the tidal component of the along-shore current just seaward of the surf zone (which transports water up-coast during flood tides and down-coast during ebb tides). The influence of the thermal boil on cross-shore transport at Huntington Beach will be described in detail elsewhere (B. H. Jones et al., manuscript in preparation, 2005).

#### 3.2.1.3. Along-Shore and Cross-Shore Flux of Dye-Labeled Water

[22] In this section we present an analysis of the in situ dye measurements collected during the TM dye injection on 1 May, 2000 with the goal of obtaining a first-order estimate of the along-shore and cross-shore flux of water in the surf

$$F_c = \int_{A_l} v_c dA \Big/ A_l. \qquad (1b)$$

[24] On May 1, 2000, 4.5 kg of dye was injected into the surf zone at the Talbert Marsh outlet (a total of 9 kg was injected into the TM outlet, and approximately 50% of that immediately entrained into the surf zone [*Grant et al.*, 2001]), and over the following two days some fraction of this dye was detected in the surf zone at several locations (i.e., 3N and 9N) up-coast of the TM outlet. We estimate the total mass of dye that passed beach station 9N by adding up the observed concentrations over time, thus:

$$M(y) = \sum F_l A_c C(y) \Delta t \qquad (2)$$

[25] The sum in equation (2) is taken over all samples collected in the surf zone at 9N, $C(y = 9N)$ represents a single observation of the dye concentration at 9N in kg/m$^3$, $F_l$ and $A_c$ are defined above, and $\Delta t$ is the time interval between sampling events ($\Delta t$ = 1 h). We assumed that along-shore flux $F_l$ is equal to the observed shore-parallel propagation velocity of dye-labeled water in the surf zone, which was estimated in section 3.2.1.1 from aerial photos of the dye fields: $F_l$ = 0.3 m/s. The width of the surf zone, $x_w$ = 50 m, is also estimated from aerial photos, and the water depth, $h_w$ = 1m, is estimated from measurements of the beach profile. The along-shore volume flow rate in the surf zone, $F_l A_c$ is thus estimated to be 8 m$^3$/s. Substituting into equation (2) values for $C(y = 9N)$, $F_l$, $x_w$, and $h_w$, we obtain the following lower-bound for the mass of dye passing surf zone station 9N: $M(y = 9N) > 0.7$ kg, a modest fraction of the original injection. Note that this estimate is a lower bound because dye measurements in the surf zone saturated as the primary dye pulse passed 9N (see lower panel of Figure 2).

[26] An estimate for the cross-shore flux $F_c$ can be obtained by combining the lower-bound for $M(y = 9N) > 0.7$ kg with a model of surf zone transport and mixing:

$$M(y) = M_0 \exp\left[\frac{-2yF_c}{x_w F_l}\right] \qquad (3)$$

where $M(y)$ is the total mass of dye passing a surf zone station located a distance $y$ down-current from the source, $M_0$ represents the mass of dye entrained in the surf zone at $y = 0$ (taken here as the outlet of the Talbert Marsh), and all other variables have been defined previously (also see Table 2). This simple model for the mass of pollutant (or tracer) passing a fixed point along the shoreline can be derived [see *Boehm*, 2003] under the assumption that mass transport in the surf zone is controlled by a steady-state balance between along-shore advection (represented by $F_l$) and cross-shore dilution (represented by $F_c$). As demonstrated in section 4.2.1 of this paper, equation (3) can also be derived using a more realistic unsteady model of surf zone fate and transport, provided that along-shore advection dominates both along-shore mixing (by longitudinal dispersion and/or turbulent diffusion) and pollutant loss from the surf zone (by cross-shore mixing and/or first-order reaction).

[27] Substituting into equation (3) values for $y = 9N$ = 2.5 km, $F_l$ = 0.3 m/s, $x_w$ = 50 m, $M_0$ = 4.5 kg, and $M(y = 9N) > 0.7$ kg, the following estimate for the cross-shore flux of surf zone water is obtained: $F_c < 0.006$ m/s. According to this calculation, the flux of surf zone water parallel to shore is >50 times larger than the flux of surf zone water cross-shore: $F_l/F_c > 50$. This result is qualitatively consistent with the aerial image in Figure 1a that shows dye from the TM outlet is highly elongated in the shore-parallel direction. An independent estimate of $F_c$, based on application of the above model to fecal indicator bacteria measurements in the surf zone, is reported later in the paper (section 3.2.2.2).

**3.2.1.4. Along-Shore Stretching of Dye Fields in the Surf Zone**

[28] Based on the areal images in Figure 1, it is clear that dye labeled water in the surf zone undergoes significant stretching in the along-shore direction. Here we show that a Fickian diffusion model adequately describes this along-shore stretching and—at least for the set of experiments reported here—along-shore mixing appears to be dominated by longitudinal dispersion.

[29] If a Fickian diffusion model applies, then the along-shore length $L$ of the dye field should increase with time thus [*Fischer et al.*, 1979]:

$$L \approx 4\sqrt{2D_{eff}t} \qquad (4)$$

where $t$ is elapsed time since the dye was injected and the effective diffusion coefficient $D_{eff} = \varepsilon + D_L$ (units of L$^2$/T) is taken as the sum of coefficients for turbulent diffusion $\varepsilon$ and longitudinal dispersion $D_L$. The lengths of dye plumes in the surf zone at various times post release (Table 1) are consistent with the predicted relationship between $L$ and $t$ in equation (4). Referring to Table 1, the predicted and observed plume lengths are in near perfect agreement for the second time point (14:30 PDT on 1 May and 15:18 PDT on 10 May), because the magnitude of $D_{eff}$ was calculated from this first set of observations. Significantly, the predicted and observed lengths for the third time point (17:33 PDT on 1 May and 16:05 PDT on 10 May) are also in close agreement. Our estimates of the along-shore mixing coefficient (40 to 80 m$^2$/s, see Table 1) are comparable to the longitudinal dispersion coefficients of 60 to 70 m$^2$/s inferred from rip current spacing and along-shore current measurements by *Inman et al.* [1971] at another southern California beach. This last observation is consistent with the idea that longitudinal dispersion dominates the along-shore stretching, and hence mixing, of mass in the surf zone.

**3.2.2. Fecal Indicator Bacteria Experiments**

**3.2.2.1. Observations of Fecal Indicator Bacteria in the Outlets and Surf Zone**

[30] Hourly measurements of fecal indicator bacteria in the surf zone and SAR and TM outlets are more-or-less consistent with the hypothesis that these tidal outlets are a source of fecal pollution in the surf zone. Fecal indicator bacteria measurements are presented in Figure 3, where the log-transformed concentrations of TC, EC, and ENT in the surf zone are denoted by color, with red roughly corresponding to California's single-sample ocean bathing water standards for the respective indicator bacteria and blue corresponding to the lower-limit of detection of the

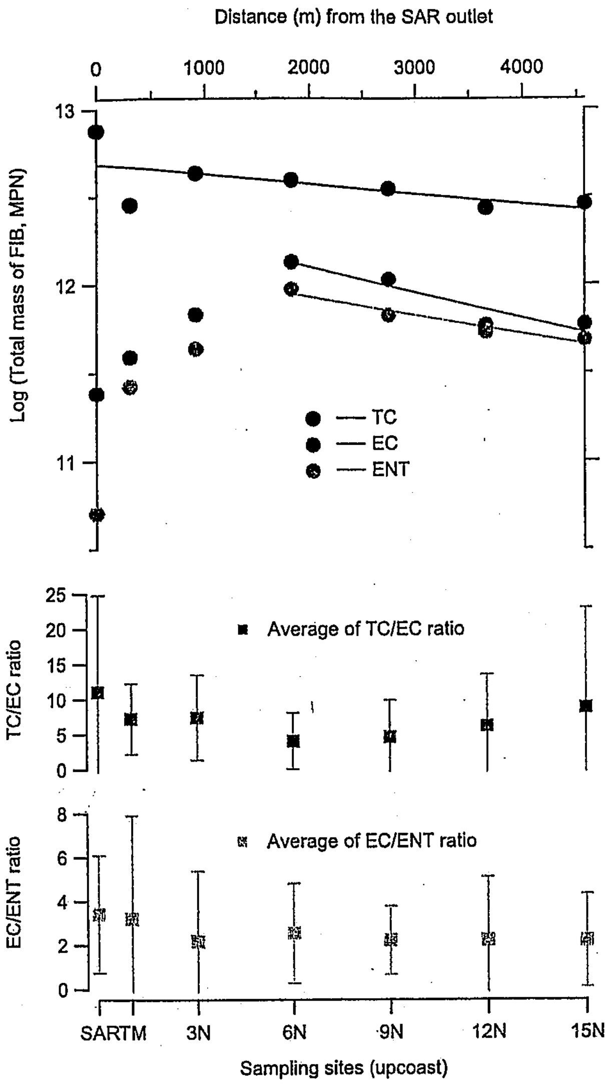


**Figure 4.** Total mass of fecal indicator bacteria that flowed out of the SAR and TM outlets, and flowed past the upcoast surf zone stations, during the 48-hour study on 5–7 July, 2001 at Huntington State Beach (top panel). Also shown are the average (and standard deviation) of two fecal indicator bacteria ratios: TC/EC (middle panel) and EC/ENT (bottom panel).

direction of tidal flow), with concentrations frequently >100 times higher on the down-coast side of the river outlet compared to the up-coast side (compare fecal indicator bacteria concentrations measured at stations W1 and W2, red and blue curves, middle panel, Figure 3). As described elsewhere [*Grant et al.*, 2002], water quality on the down-coast edge of the SAR outlet is impacted by a storm sewer drain that discharges to that side of the river. The remarkable degree of variability in fecal indicator bacteria concentrations over the river mouth, coupled with temporal and spatial variability associated with the surf zone entrainment of ebb flow from the SAR and TM tidal outlets (see section 3.2.1.1), significantly complicates the development of accurate estimates for the mass of fecal indicator bacteria entrained in the surf zone from tidal outlets.

[32] Another complication documented here is that different groups of fecal indicator bacteria exhibit different spatio-temporal patterns in the surf zone, suggesting the existence of multiple sources, and/or multiple transport pathways, for the different indicator groups. As noted elsewhere [*Kim et al.*, 2004; *Noble and Xu*, 2004], the spatio-temporal distributions of TC concentrations in the surf zone are largely consistent with the notion that, during the field experiment in July 2001, TC were entrained in the surf zone from the SAR and/or TM outlets during ebb tides, and then propagated up-coast at an average velocity not too different from the 0.3 m/s velocity observed during the first dye injection from the TM outlet (compare red streak of TC contamination with diagonal line in Figure 3). Up-coast propagation of the EC and ENT plumes is less obvious; indeed, in several cases these fecal indicator bacteria groups appear to arrive simultaneously at all stations up-coast of the SAR and TM outlets (e.g., ENT event just after midnight, 00:00 to 06:00, on 7/7) as noted by Rosenfeld et al. (submitted manuscript, 2005).

[33] Several hypotheses can be formulated to explain the different spatio-temporal patterns observed for TC, on the one hand, and EC and ENT, on the other hand. Hypothesis 3: All fecal indicator bacteria in the surf zone at Huntington Beach originate from a single source (i.e., ebb flow from the SAR and TM outlets), but these bacteria experience multiple fate and transport pathways in the ocean which, when superposed, give rise to the different spatiotemporal patterns evident in Figure 3. Hypothesis 4: There are multiple spatially distinct sources of fecal indicator bacteria in the surf zone at Huntington Beach (in addition to the SAR and TM outlets), and these different sources are characterized by different TC/EC and EC/ENT ratios. In the next several sections we quantitatively analyze the data presented in Figure 3, with the twin goals of better characterizing the along-shore and cross-shore transport processes, and testing the two hypotheses (Hypotheses 3 and 4) articulated above.

**3.2.2.2. Fecal Indicator Bacteria Mass and Cross-Shore Flux of Surf Zone Water**

[34] The top panel in Figure 4 is a plot of the total mass $M$ of fecal indicator bacteria that flowed out of the SAR and TM outlets, and flowed up-coast past surf zone stations 3N through 15N, during the forty-eight hour study in July 2001. To obtain these bacterial mass estimates, we used an approach similar to the one described above for the dye data (see equation (2), section 3.2.1.3); details of the method employed can be found at the end of this section. Comparing the total mass of bacteria flowing into the ocean during ebb tides from the two outlets (left-most data points, top panel, Figure 4), we find that SAR is a larger source of TC, TM is a larger source of ENT, and both outlets discharge approximately equivalent amounts of EC. The observation that TM is a significant source of ENT is consistent with an earlier study that identified the Talbert Marsh, and its associated flood control channels, as a source of ENT in the surf zone at Huntington Beach [*Grant et al.*, 2001].

[35] The TM and SAR outlets appear to be the primary sources of TC pollution in the surf zone at Huntington Beach. This conclusion is supported by two lines of evidence (top panel of Figure 4): 1. Over the 48 h period

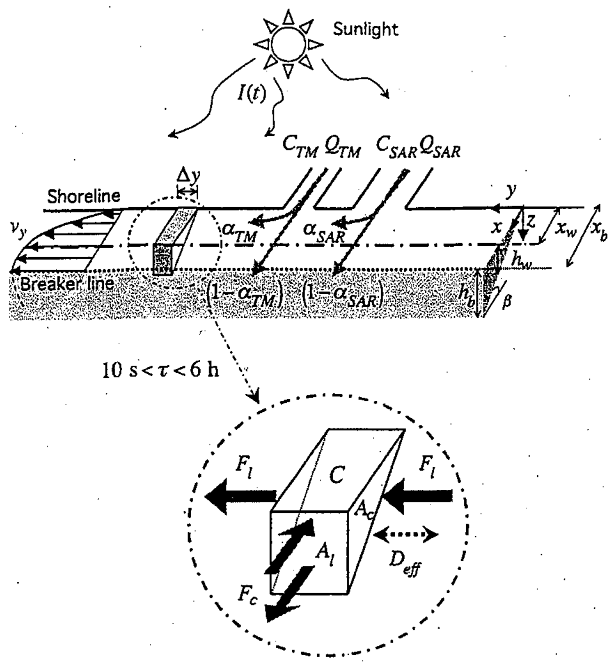


**Figure 5.** Conceptual model of the fate and transport of fecal indicator bacteria in the surf zone.

ratio, which appears to be somewhat depressed in this region. Interestingly, the average TC/EC ratio is below 10 at most of the surf zone stations at Huntington Beach. When considered in light of the *Haile et al.* [1999] study, this last result may imply a greater health risk associated with recreating in the surf zone at Huntington Beach—particularly around stations 6N and 9N—due to the high concentrations of fecal indicator bacteria present there, and the relatively low TC/EC ratios observed.

## 4. Modeling Studies

### 4.1. Methods

#### 4.1.1. Conceptualization of the Surf Zone

[40] Over the past several sections we utilized a simple steady-state model of mass transport in the surf zone to analyze data obtained from dye and fecal indicator bacteria monitoring studies. In this section we develop a more sophisticated unsteady model of surf zone transport that explicitly accounts for many of the processes identified previously as potentially affecting the concentration of fecal indicator bacteria in the surf zone, including the tidal modulated input of pollution from the SAR and TM outlets, solar modulated die-off, along-shore advection, along-shore mixing by longitudinal dispersion and/or turbulent diffusion, and cross-shore transport. Although models of pollutant transport in the surf zone have been published in a number of previous articles [*Cheng et al.*, 2000; *Inman et al.*, 1971; *Boehm*, 2003; *Steets and Holden*, 2003], none directly address the collective set of transport phenomena identified, through the field studies described earlier, as affecting fecal indicator bacteria fate and transport at Huntington Beach.

[41] For the purpose of the modeling studies described here, the surf zone is conceptualized as a prism through which mass flows both parallel and perpendicular to shore (coordinates $y$ and $x$, respectively) (Figure 5). The beach is assumed to have slope $\beta$. The variable $x_b$ represents the cross-shore distance from the shoreline ($x = 0$) to where the waves just begin to break ($x = x_b$). The variable $x_w$ represents the cross-shore distance over which pollutants are well-mixed over the depth due to the turbulence of breaking waves. In general, we expect that pollutants will not be well mixed over the entire width of the surf zone, so that $x_w < x_b$. The variables $h_b$ and $h_w$ represent the water depths at $x = x_b$ and $x = x_w$, respectively.

[42] The breaking of waves against the shore generates an along-shore current $v_l$ which, when averaged over the depth, is zero at the shoreline ($x = 0$), peaks at the break-line ($x = x_b$), and decreases to zero beyond the break-line ($x \gg x_b$) [*Bowen*, 1969; *Longuet-Higgins*, 1953, 1970a, 1970b]. The velocity profile illustrated in Figure 5 assumes that the along-shore component of the coastal current is zero although, in general, the cross-shore distribution of $v_l$ will also be influenced by the along-shore component of the coastal current seaward of the surf zone. The removal of pollutants from the surf zone by the cross-shore flux of surf zone water is represented by $F_c$ (units L/T). The results presented earlier suggested that longitudinal dispersion dominates over turbulent diffusion but, in general, both longitudinal dispersion and turbulent diffusion (as represented by $D_L$ and $\varepsilon$, units $L^2/T$) could influence the long-shore stretching and mixing of pollutants in the surf zone. Finally, the pollutants are assumed to undergo first-order decay with time, as parameterized by the rate constant $k$ (units 1/T), which can be modulated by solar irradiation $I$ (units $W/m^2$).

[43] In general, all variables described above will vary with time and position along the shoreline. However, as a starting point for this analysis we assume that these parameters vary slowly (or are constant, depending on the variable, see section 4.1.3 and Table 2) once they are averaged over a time scale $\tau$ that is large compared to the characteristic time scale associated with the variability (e.g., the significant wave period, $T \approx 10$ s), and small relative to the dominant along-shore transport time scale $T_s$. Because we are interested in characterizing the entrainment and along-shore transport of pollution from a tidal outlet, the relevant transport time scale is less than the duration of a single ebb tide, or $T_s < 6$ h. Hence, the averaging time scale $\tau$ is bracketed as follows: 10 s $\ll \tau \ll$ 6 h. Because $\tau$ is taken to be less than the period of a single ebb tide, the edge of the surf zone in our conceptual model (i.e., position $x = 0$ in Figure 5) will migrate up and down the beach with the rise and fall of the tides.

[44] In this paper, we chose to focus on pollutant transport in the region over which the pollutants are well mixed ($0 < x < x_w$). This choice was motivated by several observations. First, this region of the surf zone is sampled during routine pollution monitoring and hence our model predictions can be directly compared to existing surf zone monitoring data. Second, significant recreational bathing exposure occurs in the region of the surf zone shoreward of the breaking waves and hence the concentration of fecal pollution in this region

the $i$th time, and $\alpha_{i,j}$ represents the fraction of the tidal effluent which is entrained into the surf zone from the $j$th outlet at the $i$th time (see Figure 5 for a graphical representation of these quantities).

#### 4.1.3. Pollutant Transport in the Surf Zone: Parameter Estimation

[51] To compare model predictions with observed fecal indicator bacteria concentrations in the surf zone, model simulations were carried out for the same 48 h period covered by the 6–7 July 2001 field experiment (see Figure 3). To model this experiment, we used parameter values that were either known ($N$ = 2 for the two tidal outlets, $y_{TM}$ = 300 m and $y_{SAR}$ = 0 m for the location of the TM and SAR outlets, $\Delta t$ = 1 h for the sampling rate of fecal indicator bacteria concentrations and tidal flow rates in the TM and SAR outlets), or estimated for this period of time ($F_l$ = 0.3 m/s, $F_c = 10^{-3}$ m/s, section 3.2.2.2), or estimated from dye experiments carried out under similar wave conditions ($D_{eff}$ = 40 m$^2$/s, and $x_w$ = 50 m, $h_w$ = 1 m, sections 3.2.1.1 and 3.2.1.3) (see Table 2).

[52] Based on an analysis of the dye and fecal indicator bacteria data described in section 3, the parameters $F_l$, $F_c$, $D_{eff}$, and $x_w$ are relatively stable, within a factor of three or better. Because $h_w$ depends on $x_w$ through the beach slope–which is not expected to vary much over the time scale of our field experiments–the former parameter should also be relatively stable. The parameter that is likely to be the most variable, and about which the least is known, is the fraction $\alpha_{SAR}$ and $\alpha_{TM}$ of tidal flow from the SAR and TM outlets that is entrained in the surf zone. Dye results presented earlier suggest this parameter is highly variable, both at different outlets for a fixed time, and at the same outlet for different times (see section 3.2.1.1). For the calculations presented below, these two parameters were estimated by finding values that minimized the least-squares difference between the predicted and measured TC concentration at surf zone station 3N. The TC signal at 3N was chosen because: 1. This surf zone station is nearest the tidal outlets, and hence water quality at this site is the most likely to be influenced by bacteria flowing out of the outlets during ebb tides. 2. All available evidence supports the idea that the SAR and TM outlets are significant sources of TC in the surf zone at Huntington Beach (section 3.2.2).

[53] Finally, to account for the sunlight modulated die-off of fecal indicator bacteria (the $k$ term in equation (6b)), first-order decay was written [*Sinton et al.*, 1999]:

$$k(t) = k_{FIB}I(t) \tag{12}$$

where $I(t)$ and $k_{FIB}$ represent, respectively, measured sunlight irradiation (in units of W/m$^2$) and fecal indicator bacteria die-off rate constant (in m$^2$/Whr). Hourly measurements of total incoming solar radiation (Kipp and Zonen, CM3 Thermopile Radiometer, The Netherlands) in the nearby San Joaquin marsh were substituted for $I(t)$, and the following values were employed for the die-off rate constant of the different fecal indicator bacteria groups [*Sinton et al.*, 1999]: $k_{TC} = 1.8 \times 10^{-3}$, $k_{FC} = 1.7 \times 10^{-3}$, and $k_{ENT} = 9.7 \times 10^{-4}$ m$^2$/Whr.

#### 4.1.4. Modeling Wave-Driven Along-Shore Currents

[54] Deep water wave data were monitored during the 5–7 July 2001 fecal indicator bacteria experiment by the CDIP San Pedro Buoy [*CDIP*, 2003], Station #092, moored offshore near Huntington Beach at 33 37.070 N, 118 19.020 W where the local water depth is 457 m. The CDIP buoy data was reprocessed to yield time series (with a 30 min sampling rate) of deep water significant wave height, period and direction. These data were then used to drive the wave refraction model; specifically, waves measured at the offshore buoy were shoaled onto a 31 km reach of surf zone centered on SAR outlet. The shoaling computations were performed on a 200 × 400 point rectangular grid (3 arc-second grid cell resolution) using a refraction/diffraction code based on the parabolic equation method applied to the mild slope equations for surface gravity waves [*Kirby*, 1986; *O'Reilly and Guza*, 1991]. These shoaling computations produced estimates of breaker heights $H_b$ and angles $a_b$ at 30-minute intervals for each 120 m increment of shoreline within the wave shoaling grid. Breaker heights were calculated from stepwise refraction/diffraction computations by solving for the grid cells in which the local shoaling wave height matches the depth dependent breaker criteria [*Raubenheimer and Guza*, 1996], $H_b = \gamma h_b$, where $h_b$ is the depth of wave breaking and $\gamma$ = 0.78. The suite of local solutions for ($H_b$, $a_b$, $h_b$, $T$) allow computations of the components of the break point radiation stress tensor [*Longuet-Higgins and Stewart*, 1964], from which the along shore current profiles, $v_l(x, y, t)$, were calculated at each 120 m shoreline increment using the Bowen formulation [*Bowen*, 1969]. These calculations assumed a uniform mean beach slope tan $\beta$ = 0.02, and a *K-factor* relating the position of maximum set-up to the still-water line of $K$ = 0.4.

### 4.2. Results

#### 4.2.1. Exponential Along-Shore Decay in Pollutant Mass

[55] In section 3.2.2.2 we noted that the mass of fecal indicator bacteria flowing past a particular surf zone station appears to decay exponentially with along-shore distance from the source of contamination (either the SAR or TM outlet, or a source farther to the north around surf zone station 9N). The exponential decline of surf zone pollution with along-shore distance has been observed elsewhere [*Inman et al.*, 1971; J. Largier, personal communication] and justified theoretically using steady-state tanks-in-series [*Inman et al.*, 1971] and differential equation [*Boehm*, 2003] models of surf zone transport and dilution; indeed, the steady-state solution to the Boehm model is presented as equation (3) earlier in this paper. However, it is not clear if steady-state models are a valid approximation of the highly unsteady conditions that prevail in the surf zone. Further, these previous models focus on the decay of pollutant concentration with along-shore distance—whereas the present study is concerned with the decay of pollutant mass with along-shore distance—and they do not consider along-shore transport of mass in the surf zone by longitudinal dispersion and/or turbulent diffusion, where the latter could be important under certain conditions (e.g., when the waves break with their crests parallel to the beach). In this section we identify the conditions under which simple steady-state expressions—like equation (3)—can be used to interpret pollutant or tracer measurements in the surf zone.

[56] As was the case for the experimental observations described earlier in this paper (sections 3.2.1.3 and 3.2.2.2),

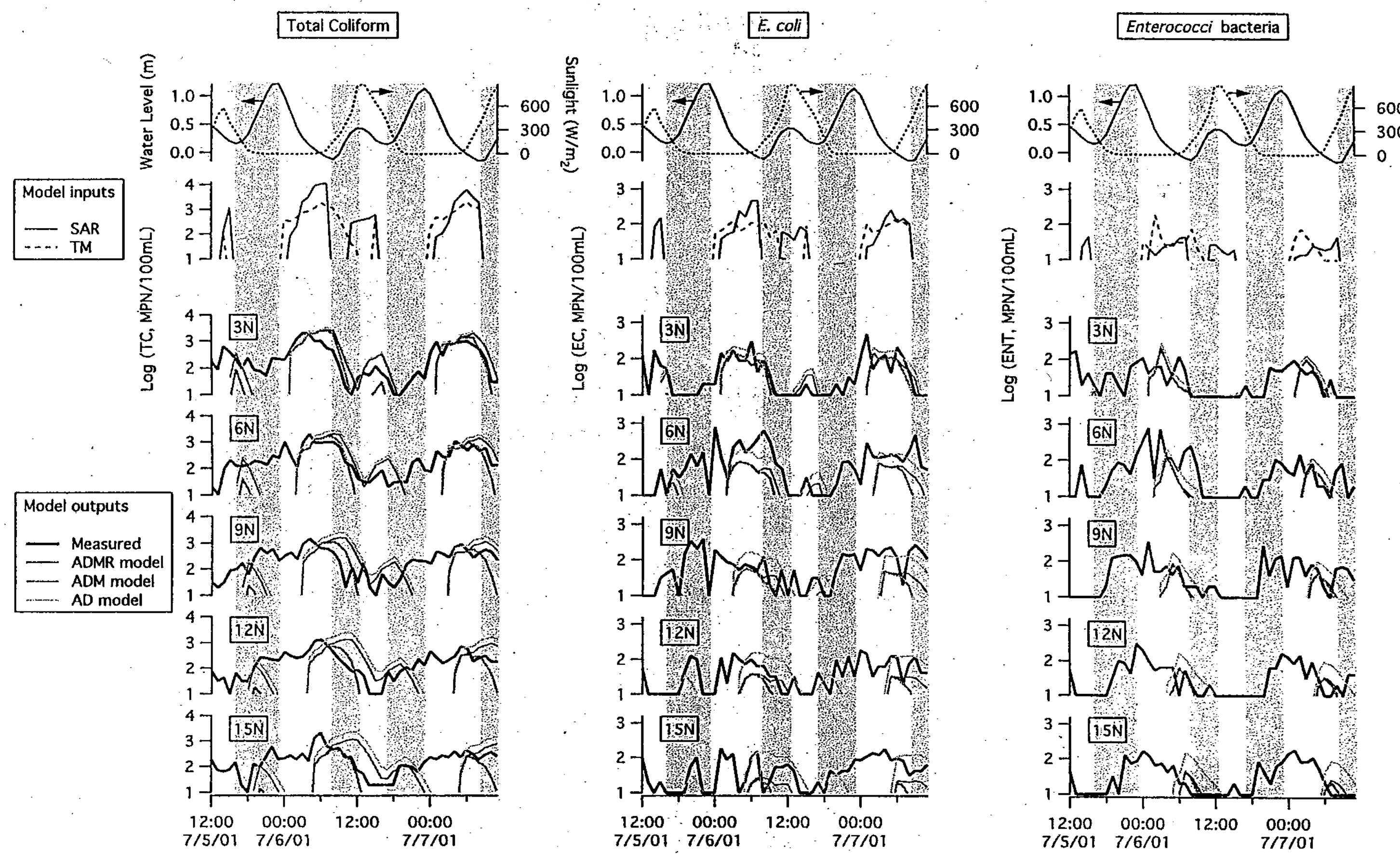


**Figure 6.** Measurements and model predictions of fecal pollution in the surf zone at Huntington Beach on 5–7 July, 2001. Top row: mean sea level measured at the TM outlet and sunlight intensity measured in the nearby San Joaquin Marsh. Second row: concentrations of fecal indicator bacteria at the Santa Ana River (solid line) and the Talbert Marsh (dashed line) outlets (note that in this plot the concentrations are set to zero during flood tides). Third–seventh row: model-predicted and observed fecal indicator bacteria concentrations at surf zone stations 3N, 6N, 9N, 12N, and 15N. The solid black line represents measured data, and the colored lines represent predictions of the ADMR (red), the ADM (blue), and the AD (yellow) models. Blue vertical stripes indicate periods of rising tide.

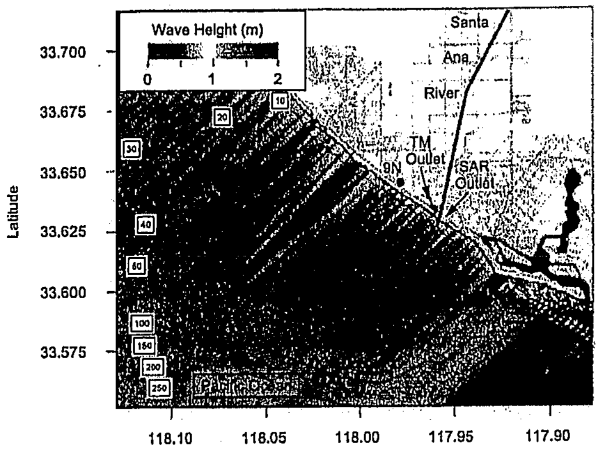


**Figure 8.** Refraction/diffraction pattern of wave field at 12:03 hours on 7 July 2001 during the dispersion study of fecal indicator organisms in the neighborhood of the Santa Ana River and Huntington Beach. Incident wave height equal to 0.60 m, period equal to 9.09 s, direction equal to 190° (from CDIP, San Pedro Buoy, Station #092).

pulsate with the arrival of each forerunner group. A continuous, steady south swell arrived in the afternoon of 6 July and persisted until the evening of 7 July [*CDIP*, 2003], with periods of $T = 9$ s and breaker heights of $H_b = 1.0–1.2$ m. Because of the steadiness of this swell, the along-shore current remained quasi-steady during this period, with mean velocities varying slowly between 0.30 and 0.45 m/s. The along-shore particle displacement in Figure 7 shows that the mean drift rate over the 48 hour period of the south swell event is 0.27 m/s, consistent with our previous estimates for the along-shore flux of $F_l = 0.3$ m/s (section 3).

[69] Figure 9 shows the alongshore variability of $v_y(x, y, t)$ and the divergence of drift $\partial v_y\ (x, y, t)/\partial y$. Both $v_y\ (x, y, t)$ and $\partial v_y(x, y, t)/\partial y$ are evaluated at $x = x_w$ at mid-day on 7 July 01, when the swell and along-shore current were fairly steady (Figure 7). To avoid spurious end effects of the refraction grid (Figure 8) only 20 km of the 31 km reach of coastline around the SAR are evaluated in Figure 9. Inspection of Figure 9 reveals that the along-shore current flows up-coast at a fairly uniform rate between SAR and 9N, with a mean of about 0.3 m/s. However, immediately north of 9N, the along-shore current slows down. The same type of along-shore variations occurs again immediately up-coast of 15N, and at both locations, the retardation in along-shore current leads to a negative divergence of drift. These non-uniformities in the along-shore currents are induced by the shadows and bright spots in the refraction/diffraction pattern (Figure 8) caused by wave shoaling over irregularities in shelf bathymetry. In particular the large shadow and adjacent bright spots found near the Huntington Beach Pier in Figure 8 are responsible for the large deceleration in along-shore current and negative divergence of drift near station 15N. Negative divergences of drift will probably increase the cross-shore mixing of contaminants into adjacent offshore waters via rip currents [*Bowen and Inman*, 1969].

[70] In summary, it is probably reasonable to assume that the along-shore drift at Huntington Beach is fairly constant, at least for the July 5–7 (2001) time frame and the particular stretch of surf zone (between the SAR outlet and surf zone station 15N) for which high frequency fecal indicator bacteria measurements are available. The along-shore current was quasi-steady for the period in question, and the mean value of 0.3 m/s agrees closely with particle drift rates calculated from the spatial and temporal variability of the shoaling wave field. However, the spatial non-uniformities that were resolved in the along-shore drift could lead to along-shore variability in the rate at which pollutants are exchanged between the surf zone and offshore. Indeed, the fact that the along-shore current decelerates around 9N and 15N implies that these areas likely experience enhanced cross-shore exchange.

## 5. Summary and Future Prospects

[71] The near shore fate and transport of dye, fecal indicator bacteria and, by inference, other contaminants, from tidal outlets at Huntington Beach appear to involve five distinct processes: 1. Highly variable surf zone entrainment of contaminants discharged to the ocean from tidal outlets during ebb tides. 2. Transport of the contaminants parallel to shore at a velocity $F_l$ (approximately equal to 0.3 m/s during the experimental realizations described above). 3. Stretching of contaminant plumes parallel to the shore by turbulent diffusion and/or longitudinal dispersion. 4. Permanent removal of contaminants from the surf zone by reaction (solar-modulated die-off in the case fecal

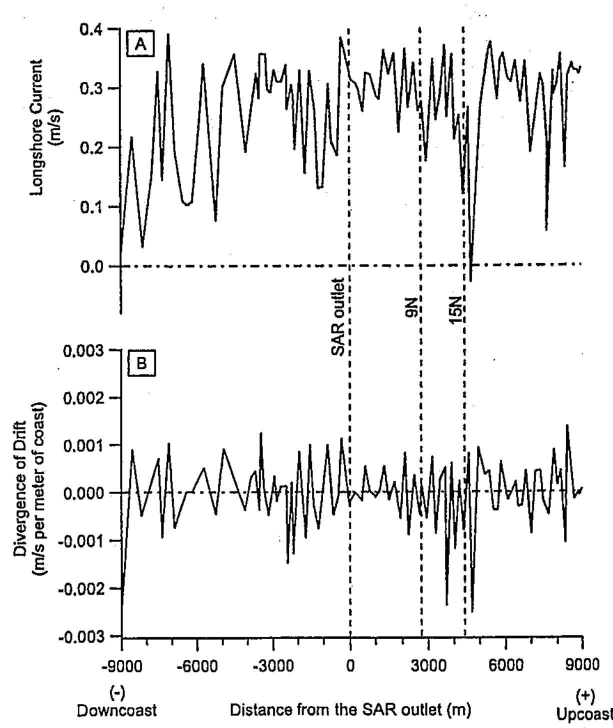


**Figure 9.** Longshore variation of drift for 7 July 2001 at 12:03 hours. (a) Longshore current at $x_w$ = 50 m; (b) divergence of drift at $x_w$ = 50 m.

just outside, of the surf zone)—precisely the same region where near shore currents appear to focus pollution from tidal outlets. The intersection of human recreation and near-shore pollution pathways implies that, from a human health perspective, special care should be taken to reduce the discharge of harmful pollutants from land-side sources of surface water runoff, such as tidal outlets and storm drains.

[80] The field data presented in this study underscore the degree to which the concentration of pollution in the surf zone varies in both space and time. While it is generally understood that fecal pollution concentrations—and hence human health risk from recreational bathing–can vary with along-shore distance from storm drains and other shoreline outfalls [*Haile et al.*, 1999; *Pruss*, 1998], the influence of temporal variability in pollution concentrations may be less appreciated. That variability includes not only sub-tidal to inter-annual variability evident from analysis of historical water quality records [*Boehm et al.*, 2002a, 2004b; *Boehm and Weisberg*, 2005], but also hour-to-hour variability that is spatially coherent over multi-kilometer stretches of the shoreline. Given that concentrations of fecal indicator bacteria at a single location in the surf zone can vary by orders of magnitude over a short period of time (ca., 6 h), the human health risk experienced by recreational bathers may be determined as much by when they go into the water, as where they go into the water. The human health implications of temporally and spatially variable concentrations of fecal pollution in the surf zone would appear to be an important avenue of future research–one that will necessitate the cooperation of oceanographers, engineers, and human health experts.

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# Public Mis-Notification of Coastal Water Quality: A Probabilistic Evaluation of Posting Errors at Huntington Beach, California

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Whenever measurements of fecal pollution in coastal bathing waters reach levels that might pose a significant health risk, warning signs are posted on public beaches in California. Analysis of historical shoreline monitoring data from Huntington Beach, southern California, reveals that protocols used to decide whether to post a sign are prone to error. Errors in public notification (referred to here as posting errors) originate from the variable character of pollutant concentrations in the ocean, the relatively infrequent sampling schedule adopted by most monitoring programs (daily to weekly), and the intrinsic error associated with binary advisories in which the public is either warned or not. In this paper, we derive a probabilistic framework for estimating posting error rates, which at Huntington Beach range from 0 to 41%, and show that relatively high sample-to-sample correlations (>0.4) are required to significantly reduce binary advisory posting errors. Public mis-notification of coastal water quality can be reduced by utilizing probabilistic approaches for predicting current coastal water quality, and adopting analog, instead of binary, warning systems.

## Introduction

Many government-sponsored environmental monitoring programs issue health advisories whenever pollutant concentrations reach levels that might pose a threat to human health. The utility of health advisory programs logically depends on their ability to disseminate timely and accurate information, in a format that is useful and easy to understand. This study examines the health advisory component of a large (statewide) shoreline water quality monitoring program in California. Health advisories take the form of warning signs that are posted at public beaches whenever shoreline water quality (as measured by fecal indicator bacteria) fails to meet one or more of seven different state standards. The California health advisory program is one of a growing number of such programs nationwide, sponsored in part by the Federal Beaches Environmental and Coastal Health Act passed by the U.S. Congress in October 2000 (*1–4*). A noteworthy aspect of the California program is its binary nature, in which information about coastal water quality is conveyed to the public by the presence or absence of warning signs on the beach during the high-use period from April 1 through October 31 of every year. This binary approach stands in contrast to other long-standing reporting programs, for example, weather forecasts, in which the information provided to the public is probabilistic in nature (*5*).

In this paper, we set out to answer several questions: (1) What is the magnitude of error associated with binary health advisories? (2) How are these error rates affected by the degree to which the concentrations of bacteria in consecutive samples are correlated? (3) Can the accuracy and effectiveness of health advisories be improved by changing the way data are collected and analyzed and/or by changing the way water quality information is conveyed to the public? To answer these questions, we develop a probabilistic framework for analyzing posting errors and compare the theory to observations of posting errors at Huntington Beach in southern California. Huntington Beach is an ideal natural laboratory to examine shoreline water quality issues because of the magnitude of the historical water quality problem, the wealth of available shoreline monitoring data, and the fact that a series of special studies have been conducted with a wide range of sampling frequencies (*6–8*).

## Public Notification of Shoreline Water Quality in California

Beginning July 1, 1999, the State of California mandated fecal indicator bacteria monitoring at all public beaches with more than 50 000 annual visitors and established seven statewide concentration standards for fecal indicator bacteria in the surf zone. When the concentration of indicator bacteria at a monitoring site exceeds any of the California standards, the local health official must post a sign warning beach goers of potential health risks associated with entering the water (*surf zone posting*). If a sewage spill is suspected, the local health official may close the surf to public access (*surf zone closure*). Four of the seven standards are single-sample standards, for which a monitoring site is considered to be out of compliance if the concentration of indicator bacteria in a single sample exceeds specified concentrations for total coliform (TC), fecal coliform (FC), and *Enterococcus* species (ENT). The California single-sample standards for TC, FC, and ENT are respectively 10 000, 400, and 104 most probable number (MPN) or colony forming units (cfu)/100 mL; a fourth single-sample standard for TC of 1000 MPN or cfu/100 mL applies when the TC/FC ratio falls below 10. The remaining standards are 30-day geometric mean standards, for which a monitoring site is considered to be out of compliance if the geometric means of TC, FC, and ENT in all samples collected within a 30-day period exceed 1000, 200, and 35 MPN or cfu/100 mL, respectively. These standards correspond, at least theoretically, to a threshold rate of bather illness of 19 cases of highly credible gastrointestinal disease for every 1000 bathers. (*3, 9–11*) There are many historical reasons for choosing this particular threshold, including the fact that it represents the background rate of gastrointestinal illness among the general population (*12*).

## Observations of Posting Errors at Huntington Beach

The surf zone posting protocols described above were adopted with the goal of conveying to the public up-to-date information about surf zone water quality. However, a post de facto comparison of posting records and water quality test results indicates that the public is often mis-notified about current water quality conditions. This point is illustrated in Figure 1A where we compare measurements of

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in which the concentration is higher during stormy El Niño winters and lower during dry La Niña winters; (6) multi-decadal patterns in which periodic large-scale investment in sewage and storm runoff infrastructure improves coastal water quality.

Monitoring programs can detect these periodic patterns only if the time interval between samples is smaller (by at least a factor of 2) as compared to the characteristic period of a particular pattern of interest (*15*). For example, samples must be collected at least every 3 h in order to detect tidal cycling because each ebb and flood tide lasts ca. 6 h. Routine monitoring programs in California, which typically sample each site once per day to once per week, can detect patterns 3–6 described above depending on the length of time over which data are available. Importantly, processes with characteristic periods less than the sampling interval cannot be detected because the water quality signal is aliased by the sampling program. The relative uncertainty associated with the water quality sampling and testing methods, which ranges up to 23% (*16*), is also a source of noise (*17*). In the next several sections, we develop and test a probabilistic model that can account for the repeating patterns and random noise inherent in water quality measurements. To make the results of the probabilistic analysis accessible to a broad audience, each section begins with the primary question to be addressed, immediately followed by the answer supported by the analysis.

## Probability of Single-Sample Exceedences

**Question:** *Can the fraction of samples violating single-sample standards be predicted from statistical features of local water quality, such as measures of central tendency and spread?* **Answer:** *The fraction of samples violating single-sample standards can be predicted from the log-mean and standard deviation of fecal indicator monitoring data, provided that the data are well described by a log-normal distribution. Furthermore, the theory predicts and observations confirm that, under certain conditions, a marginal change in water quality can lead to a substantial change in the number of signs posted at the beach.*

The probability that the concentration of bacteria in a single sample will exceed a standard ($s$) can be represented mathematically as follows:

$$P_{ex} = P[C > s] = \int_s^\infty f_C(c)\, dc \qquad (1)$$

where $C$ is a random concentration variable, $c$ is a particular realization of the random variable, and $f_C(c)$ is the probability density function for the concentration of fecal indicator bacteria in the surf zone. The exceedence probability ($P_{ex}$) is a measure of water quality: $P_{ex} \rightarrow 1$ if water quality is very poor, and $P_{ex} \rightarrow 0$ if water quality is very good.

The monitoring data at Huntington Beach conform reasonably to a log-normal distribution (based on Kolmogorov–Smirnov normality tests (*18*); maximum difference $K - S = 0.08$ at the significant level $\alpha < 0.01$) (see Figure S1 in the Supporting Information) as do monitoring data at other coastal sites throughout the world (*19–21*). Accordingly, we replaced $C$ with $\log C$ in eq 1 and substituted the Gaussian probability distribution function for $f_{\log C}(\log c)$. After simplification, the following relationship was obtained between the exceedence probability and a nondimensional variable referred to here as $S^*$:

$$P_{ex} = \frac{1}{2} \operatorname{erfc} S^* \qquad (2a)$$

$$S^* \equiv \frac{\log s - \mu_{\log C}}{\sqrt{2}\sigma_{\log C}} \qquad (2b)$$

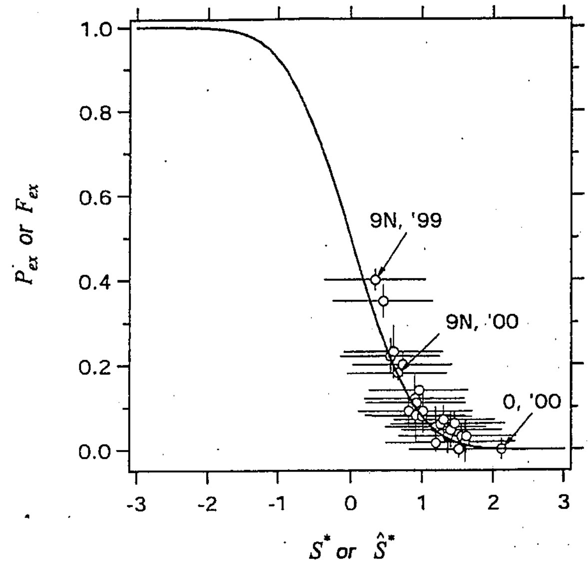


**FIGURE 2. Predicted relationship between the probability $P_{ex}$ that samples will exceed a single-sample standard and the dimensionless parameter $S^*$ (solid line, eq 2a). Data points represent observed relationship between the fraction $F_{ex}$ of samples collected at Huntington Beach that exceeded the single-sample standard for ENT plotted against the parameter $\hat{S}^*$. The vertical and horizontal error bars correspond to $\pm\sqrt{F_{ex}(1-F_{ex})/n}$ and $\pm 1/\sqrt{2}$, respectively, where $n$ is the number of data points in each data bin ($n$ = 45–65)**

In these equations, erfc is the complementary error function, and $\mu_{\log C}$ and $\sigma_{\log C}$ represent the mean and standard deviation of the log-transformed bacterial concentrations, respectively. This simple theoretical result predicts that the exceedence probability decreases with increasing values of the parameter $S^*$, ranging from $P_{ex} > 99\%$ when $S^* < -2$ to $P_{ex} < 1\%$ when $S^* > 2$ (solid line in Figure 2). In turn, the value of $S^*$ depends on local water quality ($\mu_{\log C}$ and $\sigma_{\log C}$) and the magnitude of the single-sample standard ($\log s$).

These theoretical predictions compare well with observations of single-sample exceedences at Huntington Beach. To compute the latter, summertime measurements of ENT in the surf zone at Huntington Beach were grouped, or binned, by station and year. For example, one bin constituted all ENT measurements collected at surf zone station 9N during the summer of 1999; for the purposes of this analysis, summer is defined as the time period June 1–August 31. From each data bin, we calculated the fraction $F_{ex}$ of samples that violated the single-sample standard for ENT and an empirical approximation of the parameter $S^*$ denoted here as $\hat{S}^*$ (see Supporting Information, note that the circumflex or "hat" denotes empirical approximations of population parameters). Values of $F_{ex}$ and $\hat{S}^*$ track the theoretical prediction closely (compare solid line with data points in Figure 2); hence, eq 2a appears to capture the relationship between measured water quality ($\hat{\mu}_{\log C}$ and $\hat{\sigma}_{\log C}$) and the fraction of samples that exceed a single-sample standard ($F_{ex}$). At Huntington Beach, the percentage of samples exceeding the single-sample standard for ENT ranges from a low of 0% ($F_{ex} = 0$) at surf zone station 0 during the summer of 2000 to a high of 40% ($F_{ex} = 0.4$) at station 9N during the summer of 1999 (see arrows in Figure 2).

From the shape of the theoretical curve in Figure 2, a marginal change in water quality can result in a very large or a very small change in the number of signs posted at the beach, depending on the absolute magnitude of the parameter $S^*$. In particular, eq 2a predicts that $P_{ex}$ is sensitive to marginal changes in water quality when $|S^*| < 1$ and samples, referred to here as $\hat{\rho}(1)$ (see inset in Figure 3). Empirical correlation coefficients range from $\hat{\rho}(1) = 0.04$ to 0.58; averaging across all bins, we obtain $\overline{\hat{\rho}(1)} = 0.32 \pm 0.13$. The concentration of ENT in consecutive samples are not completely uncorrelated (i.e., $\hat{\rho}(1) \neq 0$); however, the sample-to-sample correlation is sufficiently weak such that total posting error rates are indistinguishable, within the resolution of our estimates of $F^{T}_{err}$, from the predictions of Bernoulli trial theory. An exception may be the three data bins with the highest correlation coefficients: station 6N in 1998, station 3N in 1999, and station 9N in 2000 (compare red points and dashed line in Figure 3).

## Can Increasing the Sampling Frequency Reduce Posting Errors?

**Question:** *Would the sample-to-sample correlation be higher and the rate of single-sample posting errors be lower if surf zone samples were collected more frequently?*

**Answer:** *An analysis of ENT data at Huntington Beach reveals that posting decisions would have to be updated every 40 min (or more frequently) to significantly reduce posting errors. Even if posting decisions were revised every 10 minutes, when $S^*$ is close to zero as much as 30% of the signage would be in error. This result will likely apply to any shoreline site where the sampling time interval is longer than the persistence time of pollution patches in the surf zone.*

The question is motivated by the growing interest in developing rapid fecal indicator bacteria tests that could, in principle, dramatically reduce the time between when a sample is taken and the bacterial indicator concentration is known (*22*). The answer derives from an analysis of autocorrelation functions computed from four different time series (Figure 4): (1) Routine ENT monitoring data at station 9N, subsampled to yield a sampling frequency of once per week ($\Delta t = 1$ week, panel A). (2) Routine ENT monitoring data at station 9N subsampled to yield a sampling frequency of once per 3 days ($\Delta t = 3$ days, panel B). (3) A special ENT monitoring study at station 3N in which water samples were collected every hour, 24 h per day, for 2 weeks ($\Delta t = 1$ h, panel C). (4) A second special ENT monitoring study at station 6N in which water samples were collected every 10 min for a total of 12 h ($\Delta t = 10$ min, panel D) (*7*). The autocorrelation functions in Figure 4 represent the correlation $\hat{\rho}(\Delta t_j)$ between a time series and itself after introducing a lag of $j$ points or, equivalently, a time lag of $\Delta t_j = j\Delta t$. For comparison, also plotted in each panel of the figure are autocorrelation functions calculated from a sequence of random numbers ranging in magnitude from 1 to −1 (black lines in each panel).

Correlation $\hat{\rho}(\Delta t_j)$ falls off very rapidly with increasing lag $\Delta t_j$ for sampling intervals of $\Delta t = 1$ week and 3 d (red curves in panels A and B, respectively). When $\Delta t = 1$ week (panel A), a broad peak is evident at time lags of 40−50 weeks (i.e., approximate 1 yr), presumably due to the influence of seasonal rainfall on bacterial concentrations in the surf zone. Spring−neap cycling of bacterial concentration is apparent in panel B where the correlation values peak every 2 weeks. Apart from the seasonal (panel A) and spring−neap (panel B) patterns, the correlation coefficients calculated for these two cases are generally within the range calculated from a sequence of random numbers (black lines). Correlation peaks are present at multiples of 24 h when the surf zone is sampled every hour ($\Delta t = 1$ h, panel C). This diurnal cycle probably arises from the germicidal affect of sunlight (*7*), although tidal processes may also play a role (e.g., during the summer at Huntington Beach there is typically just one large ebb tide per day). Remarkably, the sign of $\hat{\rho}(\Delta t_j)$ in Figure 4C is periodically negative, implying that posting error rates might *increase* if the sampling frequency is increased, for example, from once per day to once every 12 h (see peak error rates

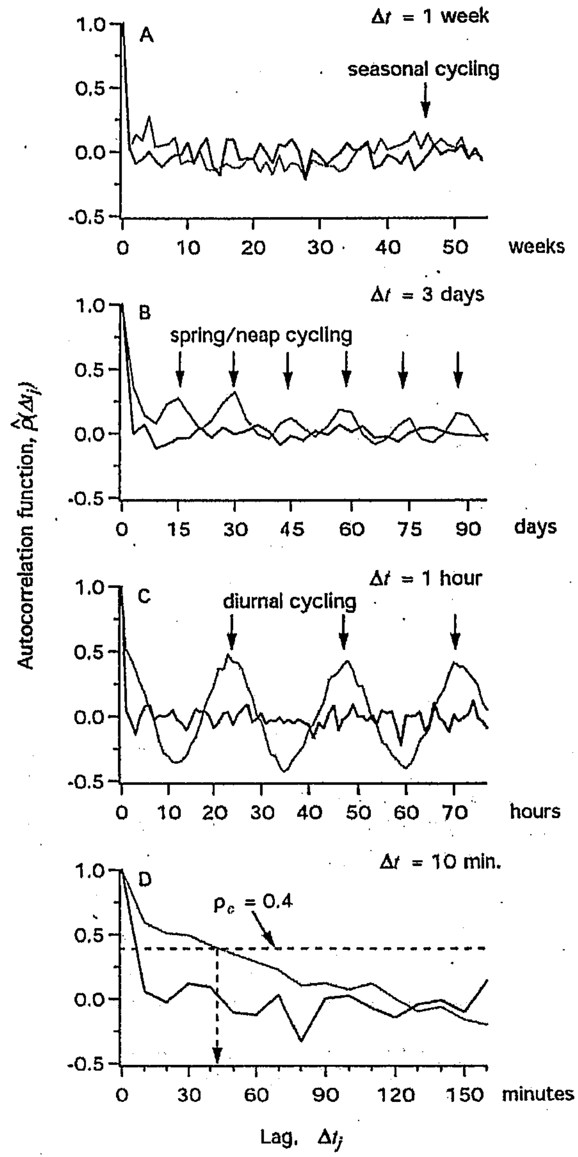


**FIGURE 4. Autocorrelation functions calculated from four different time series (red lines in each panel) and from a sequence of uncorrelated (random) numbers (black lines in each panel). The time interval between samples ($\Delta t$) is noted in each panel (see text for details). The number of samples used for the analysis in each panel is $n = 216$ (panel A), 528 (panel B), 337 (panel C), and 61 (panel D).**

when $\rho(1) < 0$ in Figure 3). Compared to the other autocorrelation functions, $\hat{\rho}(\Delta t_j)$ decays with $\Delta t_j$ more slowly when samples are collected every 10 min (panel D). Even in this case, however, the correlation coefficient for a lag of 10 min ($\hat{\rho}(\Delta t_1 = 10\text{min.}) = 0.6$) is such that substantial posting errors ($\approx 30\%$) are predicted when $S^* \approx 0$ (see Figure 3). Put another way, if the time interval between when a sample is taken and a sign is posted (or removed) was reduced to just 10 min, as much as 30% of the signage could be in error. The technology for rapid detection of fecal indicator bacteria is maturing such that near real-time measurements of these organisms may be feasible soon. Even if bacterial measurements could be carried out instantaneously (i.e., $\Delta t \rightarrow 0$ and $\rho(1) \rightarrow 1$), however, it is not clear how that information would be used in practice. Given the highly variable nature of the coastal water quality signal, health advisories would have to be updated on a minute-by-minute basis, creating an untenable

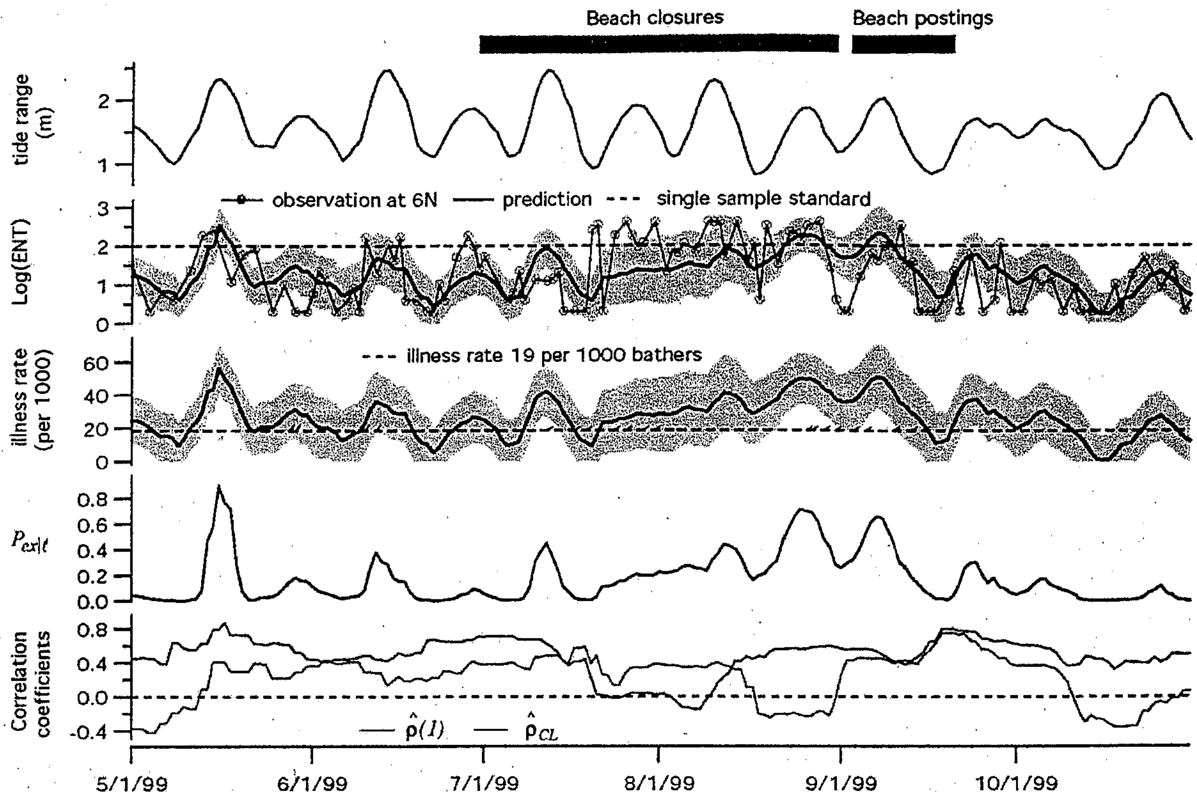


**FIGURE 5. Time series plots of maximum daily tide range (top panel), now-casts of ENT concentration (blue line, second panel), illness rates (blue line, third panel), and probability of exceeding the single-sample standard for ENT (black line, fourth panel) at surf zone station 6N in Huntington Beach. Blue bands in second and third panels represent ±1 SD (see eqs 5c and 6b); red curve in second panel is actual measurements of ENT at 6N. Bottom panel is a plot of the correlation coefficients between ENT in consecutive samples ($\hat{\rho}(1)$) and between ENT and maximum daily tide range ($\hat{\rho}_{CL}$).**

horizontal line), peaking at about 60 excess illnesses per 1000 bathers; these illness attack rates are in the range estimated by other researchers for the Huntington Beach area (*26*). Now-casts for the exceedence probability (fourth panel) exhibit spring–neap cycling, and importantly, periods of high exceedence probability (e.g., $P_{ex|t} > 0.2$) generally coincide with single-sample violations (compare second and fourth panels, Figure 5). The last panel in the figure is a plot of the correlation coefficient between ENT concentrations in consecutive samples ($\hat{\rho}(1)$, red line) and between ENT concentration and maximum daily tide range ($\hat{\rho}_{CL}$, blue line). These two coefficients were updated every day in the 6-month period encompassed by Figure 5, using ENT and maximum daily tide range data collected (ENT) or calculated (tide range) over the previous 30 d. In general, $\hat{\rho}_{CL}$ is larger than 0.4 (i.e., $\hat{\rho}_{CL} > \rho_C$, see earlier) and larger than the correlation between the concentrations of bacteria in consecutive samples ($\hat{\rho}_{CL} \geq \hat{\rho}(1)$). The exception is an approximately 1-month period, centered around August 1, when $\hat{\rho}_{CL} \approx 0$. Not surprisingly, this was also the period when our now-cast model performed least well. In general, at Huntington Beach, the current concentration of bacteria at a particular surf zone station is more correlated with the maximum daily tide range than with the concentration of bacteria in the last sample.

The model presented above could be improved by utilizing all physical variables known through past experience to correlate with coastal water quality and/or by adopting alternative now-casting methodologies (e.g., artificial neural networks (*27–29*)) that tolerate nonlinear relationships between dependent and independent variables. As mentioned above, the ideal advisory system will be analog in nature; however, even if the current binary approach is retained, posting decisions based on now-cast methodologies, like the one described here, would be an improvement over the status quo. If the now-casts of ENT presented in Figure 5 had been used as the basis for posting decisions at Huntington Beach during the summer of 1999, for example, the total posting error rate there would have been reduced between 7.5% and 50% (depending on the particular surf zone station of interest).

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## Supporting Information Available

Mathematical derivations and additional data. This material is available free of charge via the Internet at http://pubs.acs.org.

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# Scaling and Management of Fecal Indicator Bacteria in Runoff from a Coastal Urban Watershed in Southern California

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This paper describes a series of field studies aimed at identifying the spatial distribution and flow forcing of fecal indicator bacteria in dry and wet weather runoff from the Talbert watershed, a highly urbanized coastal watershed in southern California. Runoff from this watershed drains through tidal channels to a popular public beach, Huntington State Beach, which has experienced chronic surf zone water quality problems over the past several years. During dry weather, concentrations of fecal indicator bacteria are highest in inland urban runoff, intermediate in tidal channels harboring variable mixtures of urban runoff and ocean water, and lowest in ocean water at the base of the watershed. This inland-to-coastal gradient is consistent with the hypothesis that urban runoff from the watershed contributes to coastal pollution. On a year round basis, the vast majority (>99%) of fecal indicator bacteria loading occurs during storm events when runoff diversions, the management approach of choice, are not operating. During storms, the load of fecal indicator bacteria in runoff follows a power law of the form $\mathscr{L} \sim Q^n$, where $\mathscr{L}$ is the loading rate (in units of fecal indicator bacteria per time), $Q$ is the volumetric flow rate (in units of volume per time), and the exponent $n$ ranges from 1 to 1.5. This power law and the observed range of exponent values are consistent with the predictions of a mathematical model that assumes fecal indicator bacteria in storm runoff originate from the erosion of contaminated sediments in drainage channels or storm sewers. The theoretical analysis, which is based on a conventional model for the shear-induced erosion of particles from land and channel-bed surfaces, predicts that the magnitude of the exponent $n$ reflects the geometry of the stormwater conveyance system from which the pollution derives. This raises the possibility that the scaling properties of pollutants in stormwater runoff (i.e., the value of $n$) may harbor information about the origin of nonpoint source pollution.

## Introduction

A growing number of the nation's rivers, estuaries, and coastlines are impaired for fecal indicator bacteria (*1–3*). This problem is particularly acute in southern California, where the shedding of fecal indicator bacteria and pathogens from urbanized watersheds routinely triggers swimming advisories at coastal saltwater and inland freshwater beaches and the closure of shellfish harvesting areas in estuarine and coastal systems. There are many different management strategies that can be implemented to reduce the downstream impacts of fecal indicator bacteria pollution; however, it is unlikely that any single approach will be effective at all urban sites and under all environmental conditions. The goal of this study was to provide baseline data for watershed managers on the occurrence patterns and shedding rates of fecal indicator bacteria from an urban coastal watershed. The field investigations focused around the Talbert watershed that is thought to play a role in the beach postings and closures at Huntington State Beach, a popular swimming resort in southern California, as described in a companion paper (*4*) and an earlier study (*5*). This watershed, like many in southern California, has separate storm and sanitary sewer systems. Prior to 1999, both dry and wet weather runoff from the Talbert watershed drained to the ocean through a series of gutters, forebays, and channels (*6*). After 1999, local agencies began diverting dry weather runoff to the sanitary sewer system for treatment in an attempt to reduce the downstream impacts of fecal indicator bacteria on coastal water quality at Huntington State Beach (*7*). In this paper, we describe three years of data collection in and around the Talbert watershed that collectively answer the following questions: (1) How does the concentration of fecal indicator bacteria in this watershed vary spatially and temporally during dry weather and in response to storms? (2) How effective is the current management strategy of diverting dry weather runoff to the sanitary sewer system? (3) How does the load of fecal indicator bacteria scale with runoff volume? (4) What role does sediment erosion play in the loading of fecal indicator bacteria? (5) What are the management implications of these results?

The paper is organized as follows. A description of the field site is presented, followed in the next section by the methods and materials employed in the field investigations. Results and discussion of the field experiments are then presented. Next, we show that the loading of fecal indicator bacteria closely follows a theoretical model, which assumes that the bacteria originate from the shear-induced erosion of contaminated sediments. The paper concludes with a discussion of the management implications of the field data and theoretical results presented in the paper. To make the results of the paper accessible to a wide audience, we begin some sections with the primary questions to be addressed, immediately followed by answers supported by the data and analysis.

## Field Site

The Talbert and Lower Santa Ana watersheds encompass 80 km² of urban landscape in the cities of Huntington Beach,

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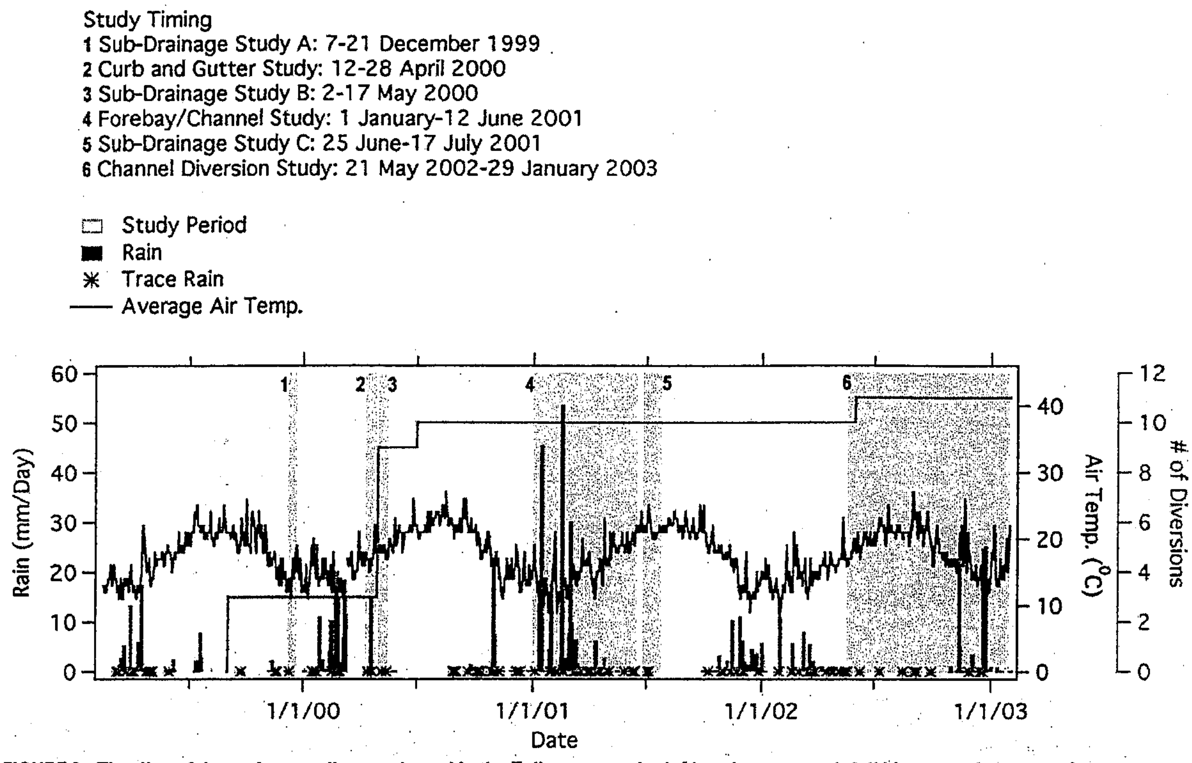


**FIGURE 2. Timeline of the various studies conducted in the Talbert watershed. Also shown are rainfall history and average air temperature recorded at the nearby John Wayne Airport and the number of forebay and channel diversion structures operating within the study area.**

**TABLE 2. Study Methods Summary**

| study | fecal bacteria methods[a] | physical properties methods[b] | no. of samples | study timing | sample collection frequency |
|---|---|---|---|---|---|
| sub-drainage study A | | | | 12/7–21/99 | |
| forebays | 1 | | 49 | | daily |
| coastal outlet | 1 | A | 805 | | hourly |
| sub-drainage study B | | | | 5/2–17/00 | |
| forebays | 1 | A | 124 | | daily |
| tidal channels | 1 | A | 30 | | daily |
| coastal outlet | 1 | A | 697 | | hourly |
| sub-drainage study C | | | | 6/25–7/17/01 | |
| forebays | 1 | B | 439 | | daily |
| tidal channels | 1 | B | 130 | | daily |
| coastal outlet | 1 | B | 508 | | hourly |
| curb & gutter study | | | | 4/12–28/00 | once/study |
| water samples | 2 | | 283 | | |
| sediment samples | 4 | | 36 | | |
| channel & forebay study | | | | | |
| forebays | 1 | B | 217 | 1/11–6/12/01 | daily |
| tidal channels | 1 | B | 111 | 1/11–6/12/01 | daily |
| bacteria forebay profile | 1 | C | 108 | 3/6–6/6/01 | weekly |
| physical forebay profile | | D | 782 | 3/6–6/6/01 | daily |
| channel diversion study | 3 | | 90 | 5/21/02–1/29/03 | triweekly |

[a] Method 1: Samples were analyzed for total coliform (TC), *E. coli* (EC), and *Enterococci* bacteria (ENT) using defined substrate technology commercially known as Colilert and Enterolert (IDEXX, Westbrook, ME). Method 2: Samples were analyzed for ENT by membrane filtration and for TC and fecal coliform (FC) by fermentation. Method 3: Samples were analyzed for TC and FC by membrane filtration and for ENT by fermentation. Method 4: Sediment samples were analyzed for TC, FC, and ENT by fermentation. [b] Method A: The conductivity and turbidity of the water samples were measured using a Thermo Orion 160 conductivity meter (Beverly, MA) and a HACH 21000N (Loveland, CO), respectively. Method B: The conductivity and turbidity of the water samples were measured using Thermo Orion 162A conductivity meter (Beverly, MA) and a DRT-15CE (Fort Meyers, FL), respectively. Method C: Turbidity measurement was made using a DRT-15CE (Fort Meyers, FL). Method D: The conductivity, temperature, pH, and dissolved oxygen were measured in-situ with a YSI (Yellow Springs, OH) 600 xl multi-parameter water quality sonde connected to an ISCO (Lincoln, NE) 4250.

**Curb and Gutter Study.** The goal of this study was to measure the concentration of fecal indicator bacteria in dry weather runoff from various locations in the watershed. Over the period April 12–28, 2000, samples of dry weather runoff were collected from 283 sites in the Talbert watershed (light blue dots in Figure 1) and surrounding area and analyzed for

**TABLE 3. Concentrations of Fecal Indicator Bacteria Measured in Samples of Dry Weather Runoff and Sediment (Sed) from Talbert Watershed (Curb and Gutter Study**

| | TC[a] | | FC[a] | | ENT[a] | | no. of samples | |
|---|---|---|---|---|---|---|---|---|
| land-use | runoff[b] | Sed[c] | runoff[b] | Sed[c] | runoff[b] | Sed[c] | runoff | Sed |
| residential | 42, (44, 190)[d] | 1440 (3564, 224 730) | 2.9 (2.6, 14)[d] | 1.8 (42, 6658) | 5.6 (5.1, 17)[d] | 1530 (422, 12598) | 150 | 7 |
| agricultural | 27, (3.7, 77) | 4500 (1696, 13 410) | 0.75 (0.4, 6) | 90 (49, 3148) | 1.6 (0.5, 7) | 99 (181, 12598) | 6 | 7 |
| commercial | 26 (33, 166) | 9459 (583, *) | 1.2 (1.2, 9) | 279 (99, *) | 1.75 (1.8, 6) | 60 (42, *) | 52 | 2 |
| industrial | 17 (16, 0) | 450000 (*, *) | 3 (3, 0) | 36000 (*, *) | 11.1 (6.8, 0) | 3330 (*, *) | 3 | 1 |
| channels | 0.6 (1, 1.2)[e] | 2070 (1321, 4860) | 0.1 (0.2, 0.25)[e] | 50 (56, 2563) | 0.1 (0.2, 0.6)[e] | 230 (243, 18311) | 25 | 8 |
| parks | 0.7 (2.1, 17)[e] | 4500 (3803, 17 325) | 0.1 (0.1, 0.1)[e] | 99, (41, 179) | 0.1 (0.2, 0.69)[e] | 99 (57, 580) | 11 | 5 |
| other | 20 (22, 88) | 8100 (11 516, 701 368) | 0.5 (0.8, 5.1) | 99 (42, 380) | 1.7 (1.8, 10) | 58 (46, 2162) | 36 | 6 |
| all | 19 (15, 118) | 4500 (3140, 20 475) | 0.7 (1, 8.8) | 95 (58, 516) | 2.4 (1.8, 11) | 99 (155, 2874) | 283 | 36 |

[a] Median (geometric mean, inner quartile region) all values × 1000. An asterisk (*) indicates insufficient data. [b] TC and FC units of cfu/100 mL of water; ENT units of MPN/100 mL of water. [c] Units of MPN/100 g of wet sediment. [d] Significantly greater than all other land-use categories in a given year ($p < 0.05$, Kruskal–Wallis), based on comparing the median of each land-use to the median computed from measurements of all other land-uses. [e] Significantly less than all other land-use categories in a given year ($p < 0.05$, Kruskal–Wallis), based on comparing the median of each land-use to the median computed from measurements of all other land-uses.

**Answer:** *The concentration of fecal indicator bacteria in dry weather runoff (1) varies systematically across an inland-to-coastal gradient, with the highest concentrations at inland sites harboring low-salinity runoff and the lowest concentrations at coastal sites harboring variable mixtures of urban runoff and ocean water; (2) is highest in runoff from residential land-use and lowest in runoff from parks; (3) exhibits significant day-to-day and year-to-year variability; and (4) is poorly correlated with turbidity. During storms, rainfall intensity is positively correlated with both concentration of fecal indicator bacteria and turbidity. Fecal indicator bacteria are present at high concentrations in sediments collected from the storm drain infrastructure.*

The answer above is based on the collective results of the curb and gutter study, the three sub-drainage studies (A–C), and the channel and forebay study as described below.

*Curb and Gutter Study.* The results are summarized in Table 3. The concentration of fecal indicator bacteria in dry weather urban runoff are very high (geometric means of 15 000, 1000, and 1800 cfu/100 mL for TC, FC, and ENT, respectively). By way of comparison, the 30-d geometric mean standards for coastal beaches in California are 1000, 200, and 35 cfu/100 mL. When sorted by land-use, the median concentration of all three fecal indicator bacterial groups is highest in runoff from residential sites ($p < 0.05$, Kruskal–Wallis). The median concentrations of one or more groups of fecal indicator bacteria are significantly lower in runoff from parks and channels ($p < 0.05$, Kruskal–Wallis). The fecal indicator bacteria concentrations in the sediment samples are also very high (geometric means of 63 000, 1000, and 3000, MPN/100 g for TC, FC, and ENT, respectively). However, no single category of land-use stands out as having significantly higher or lower sediment concentrations of fecal indicator bacteria ($p > 0.05$, Kruskal–Wallis).

*Sub-Drainage Studies (A–C).* Forebays in the Talbert watershed receive dry weather runoff from a well-defined area, as indicated by the sub-drainage boundaries drawn in Figure 1. Residential areas dominate the land-use in all of the sub-drainages of the Talbert watershed (Table 1). During dry weather periods, forebay runoff harbors very high concentrations of fecal indicator bacteria, although no single forebay (or set of forebays) is consistently higher than the rest (Table 4). For example, the median concentration of TC was highest in the Atlanta forebay during study A (in 1999), in the Adams forebay during study B (in 2000), and in the Meridith forebay during study C (in 2001). Moreover, the different fecal indicator bacteria in groups are highest in different forebays. During study A, for example, TC and EC were highest in the Atlanta forebay, while ENT was highest in the Banning forebay. These two observations—that the concentrations of fecal indicator bacteria in dry weather runoff are high in all forebays and that there is no single forebay where the concentrations are always highest—are consistent with the relative predominance of residential land-use in the Talbert watershed sub-drainages (Table 1) and the high concentration of fecal indicator bacteria detected in residential runoff during the curb and gutter study (Table 3).

During dry weather, the concentrations of fecal indicator bacteria in surface water vary systematically across an inland-to-coastal salinity gradient. The concentrations are highest in forebays and channel sites that harbor low-salinity urban runoff, intermediate at forebay and channel sites that harbor a variable mixture of runoff and ocean water, and lowest at the coastal outlet (Figure 3). The inland-to-coastal fecal indicator bacteria gradient increased from 1999 to 2001 as progressively more dry weather runoff from the Talbert watershed was diverted to the sanitary sewer system (see Table 5). Referring to Table 5, over the 3-yr study period the concentrations of fecal indicator bacteria in the forebays increased nearly an order of magnitude, while concentrations of fecal indicator bacteria at the outlet remained constant or declined slightly. When all forebay, channel, and outlet data collected during studies A–C are included, the Spearman's correlation coefficients calculated between salinity and fecal indicator bacteria are −0.65 (TC), −0.50 (EC), and −0.49 (ENT) (all significant at $p < 0.01$). For the entire data set (including the forebay, channel, and outlet samples), there is also a weak to moderate positive correlation between turbidity and fecal indicator bacteria: 0.58 (TC), 0.45 (EC), and 0.38 (ENT) (all significant at $p < 0.01$). The correlation between fecal indicator bacteria and turbidity is much weaker if only measurements on forebay samples are considered: −0.08 (TC), 0.2 (EC), and 0.32 (ENT) (EC and ENT significant at $p < 0.01$). The relatively weak correlation between fecal indicator bacteria and turbidity in the dry weather runoff is apparent in Figure 3, where the turbidity of each sample is denoted by color ranging from blue (low turbidity) to red (high turbidity).

The increase in the inland-to-coastal fecal indicator bacteria gradient during studies A–C merits discussion. Over the course of these three studies, the concentration of fecal indicator bacteria in the forebays steadily increased, while the concentrations in the channels and outlets remained constant or decreased slightly (see Table 5 for significance values). Environmental conditions that may have triggered the increasing concentration of fecal indicator bacteria in the forebays include ambient air temperature and/or the total rainfall that preceded the dry weather studies. In

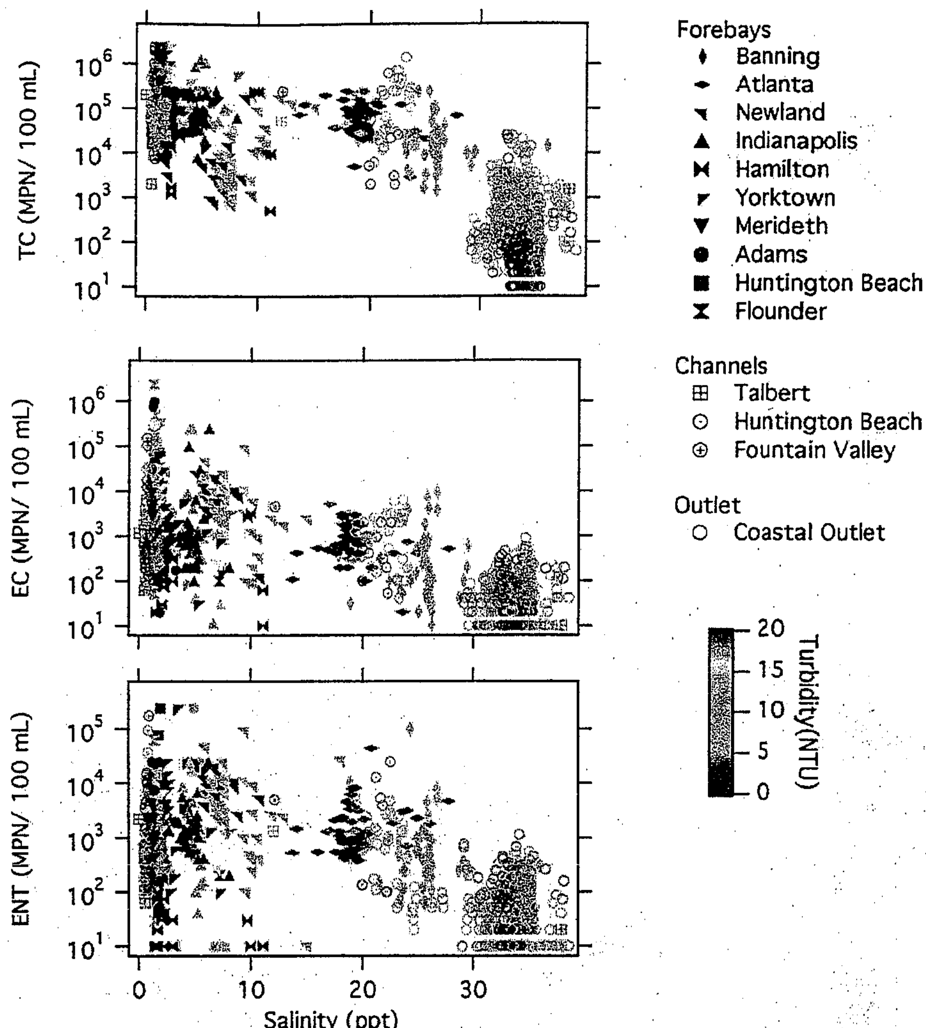


**FIGURE 3. Concentration of fecal indicator bacteria and turbidity measured in forebays and channels and at the coastal outlet of the Talbert watershed, during a series of dry weather studies conducted from 1999 to 2001 (sub-drainage studies A–C).**

**TABLE 5. Concentration of Fecal Indicator Bacteria Measured on an Inland-to-Coastal Salinity Gradient. (Sub-Drainage Studies)**

| | study A (1999) | study B (2000) | study C (2001) |
|---|---|---|---|
| | | TC (MPN/100 mL)[a] | |
| forebays | 24.2 (28.2, 146)[c] | 51.7 (52.7, 107.2)[c] | 104.6 (85.7, 213.4) |
| tidal channels | nd[d] | 36.5 (47, 109) | 38.6 (19.5, 240.5) |
| coastal outlet | 0.1 (0.1, 0.1)[c] | 0.2 (0.2, 0.3)[c] | 0.3 (0.2, 0.5) |
| | | EC (MPN/100 mL)[a] | |
| forebays | 0.3 (0.2, 0.6)[c] | 1 (1, 2.7)[c] | 1.5 (1.7, 5.3) |
| tidal channels | nd | 0.6 (0.8, 3)[b] | 0.3 (0.3, 1.9) |
| coastal outlet | 0.02 (0.02, 0.03)[c] | 0.05 (0.05, 0.1)[b] | 0.03 (0.03, 0.05) |
| | | ENT (MPN/100 mL)[a] | |
| forebays | 0.2 (0.2, 0.3)[c] | 1.2 (1.3, 4.8) | 1.3 (1.3, 3.7) |
| tidal channels | nd | 1.6 (1.2, 2.5)[b] | 0.2 (0.2, 1.2) |
| coastal outlet | 0.03 (0.03, 0.04)[c] | 0.04 (0.04, 0.08)[b] | 0.01 (0.02, 0.02) |

[a] Median (geometric mean, inner quartile region) all values × 1000. [b] Significantly greater than the subsequent year ($p < 0.05$, Kruskal–Wallis). [c] Significantly less than the subsequent year ($p < 0.05$, Kruskal–Wallis). [d] No data.

**Effectiveness of Dry Weather Diversions.**
**Question:** *How effective is the current management strategy of diverting dry weather runoff to the sanitary sewer system?*
**Answer:** *The efficacy of the dry weather runoff diversion program is mixed. On one hand, the diversions are effective at reducing the flow of fecal indicator bacteria, and presumably other contaminants associated with urban runoff, into the ocean during dry weather periods. On the other hand, on a year-round basis, the vast majority (> 99%) of fecal indicator bacteria is shed during rainstorms when diversions are not operating. Hence, while diversions appear to reduce the flow of fecal indicator bacteria to the ocean during dry weather periods when the vast majority of the people are at the beach,*

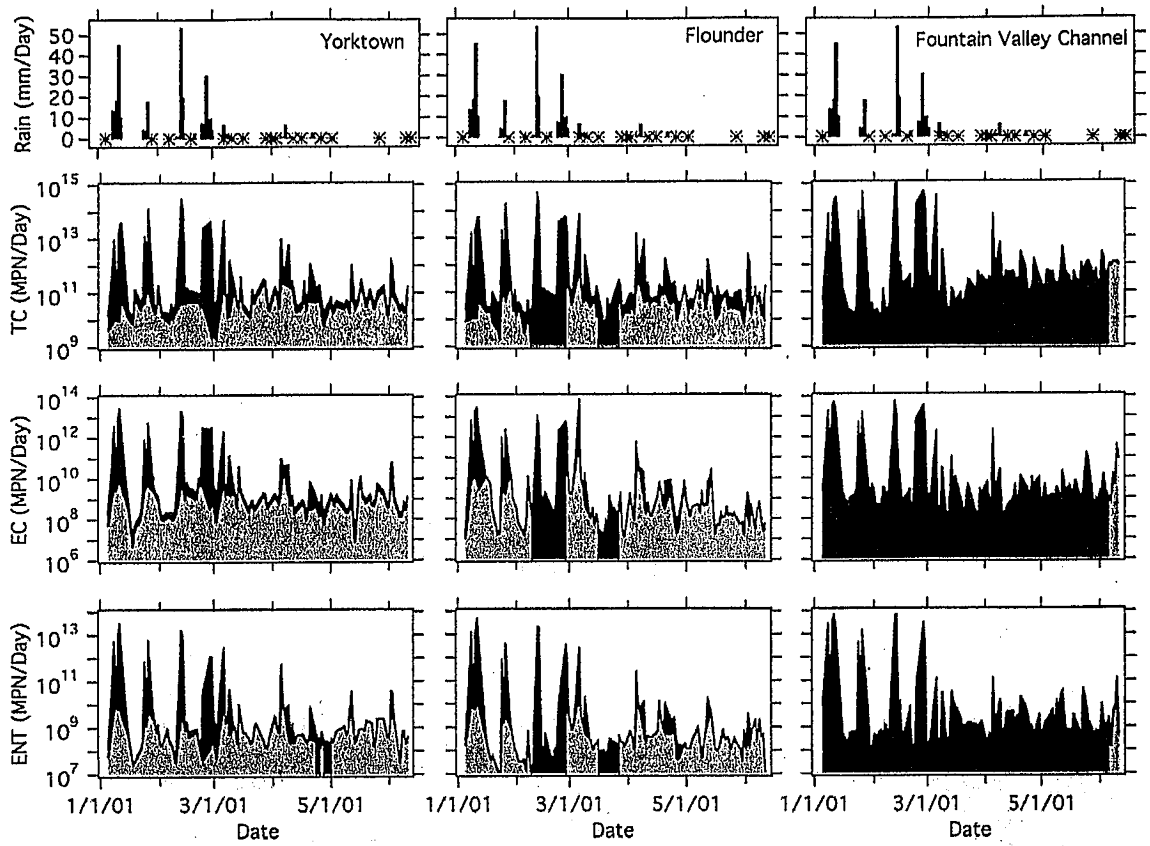


**FIGURE 5. Instantaneous loading of fecal indicator bacteria from the Yorktown, Flounder, and Fountain Valley sub-drainages during dry and wet weather (channel and forebay study). Shading denotes fraction of load diverted to the sanitary sewer system (light gray) and fraction released to the ocean (black). Also shown (top panels) are rainfall intensity (solid bars) and trace rainfall events (asterisks).**

late in the storm season and was preceded by a short (5-d) dry period (March 6, 2001, Figure 5).

Because the build-up/wash-off model is widely employed in surface water quality modeling (*20, 21*), it is important to explore what other process may be at work in our system. One alternative model envisions that most of the pollution shed during storms originates from the erosion of contaminant-laden particles (from pavement erosion, automobile grease and dirt, atmospheric particle deposition, yard and soil erosion, etc.) previously deposited on the urban landscape and in the storm sewer system. The accumulation of contaminated particulates in sewer collection systems has been implicated, by other researchers, as a source of downstream pollution during storm events. For example, a significant fraction of suspended solids, volatile suspended solids, and $BOD_5$ in storm runoff from catchments in Paris, France, appear to originate from the erosion of in-sewer sediments (*22, 23*). Furthermore, fecal indicator bacteria accumulate, die-off, and perhaps grow in storm sewer sediments (*24*). Relative to our study, evidence that fecal indicator bacteria in storm runoff originate from the erosion of contaminated sediment includes the positive correlations between turbidity, fecal indicator bacteria, and rainfall observed during the 6-month study (channel and forebay study), and the relatively high concentrations of fecal indicator bacteria measured in sediments collected from drainage channels in the Talbert watershed (curb and gutter study). In addition, the scaling of fecal indicator bacteria loading with volumetric flow rate (eq 1) is consistent with an erosion source for these pollutants, as described in the next sections. Relative to measurements conducted in forebay samples during sub-drainage studies A–C, it is interesting to note that while there is a strong positive correlation between fecal indicator bacteria concentration and turbidity during storms (Spearman's correlation coefficients of 0.63–0.67), the correlation is much weaker during dry weather periods (Spearman's correlation coefficients of −0.08 to 0.32). This observation together with the fact that the concentrations of fecal indicator bacteria in dry weather runoff are frequently very high when there should be little or no erosion of sediments (see Figure 3) suggest that different processes may drive fecal indicator bacteria concentrations during dry and wet weather.

## Sediment Erosion Model for the Loading of Fecal Indicator Bacteria during Storms

**Question:** *How does the load of fecal indicator bacteria scale with storm runoff volume? What role does sediment erosion play in the loading of fecal indicator bacteria during storms?*

**Answer:** *Fecal indicator bacterial loads scale as a power law of runoff volume, with exponent values ranging from $n = 1$ to 1.5. This observation is consistent with a simple theoretical model that assumes fecal indicator bacteria in storm runoff originate from the erosion of contaminated sediments. The model predicts that the magnitude of the power law exponent n harbors information about the geometry of the storm conveyance system from which the pollution derives. When applied to fecal indicator bacteria loads from the Talbert watershed, the magnitude of the exponents are consistent with the following hypotheses: (i) the coliform group (TC and EC) derives from the erosion of sediments in the piping and channels of the storm sewer system and (ii) ENT originates from the erosion of sediments on the surface of urban landscapes (e.g., streets, residential yards, etc.). Further research*

$\geq 0$), eqs 6a and 6b yield the following bounds on the power law exponent *n*:

$$1 \leq n \leq 1.68 \qquad (7)$$

The two bounds correspond to limiting cases for the geometry of the conveyance system. Specifically, the lower bound ($n = 1$) applies to the case where the hydraulic radius is relatively insensitive to changes in flow rate (i.e., $r \approx 0$); the upper bound ($n = 1.68$) applies to the case where the wetted perimeter is relatively insensitive to changes in flow rate (i.e., $p \approx 0$). If the conveyance system is an open channel, these two limits correspond to an extremely narrow channel ($n = 1$) and an extremely wide channel ($n = 1.68$), respectively.

On the basis of the analysis above, a power law relationship between pollutant loading and flow rate is expected in the case where pollutants associated with bed sediments are mobilized during storms by bed shear. Furthermore, the magnitude of the exponent *n* may contain information about the origin of the pollutant within the watershed or sub-drainage. In the case where the pollutants originate from the erosion of sediments in piping and channels associated with the storm sewer system, the hydraulic radius may be relatively insensitive to flow rate; hence, the power law exponent might be closer to the lower bound ($n = 1$). In the case where the pollutants originate as overland sheet flow (e.g., street and pavement runoff), one might expect that the wetted perimeter will be invariant, or nearly so, with flow rate; hence, the power law exponent should be closer to the upper bound ($n = 1.68$).

In the case of fecal indicator bacteria released from sub-drainages in the Talbert watershed, the observed range of values for the power law exponent ($n = 1-1.5$) are within the range predicted by our simple erosion model ($n = 1-1.68$). Intriguingly, the exponents for TC and EC ($n = 1-1.2$) are closer to the lower bound, while the exponent for ENT ($n = 1.5$) is closer to the upper bound. One possibility is that the coliform group of organisms (TC and EC) originate from the erosion of sediments in the piping and channels of the storm sewer system, while ENT originates from the erosion of sediments on the surface of urban landscapes (e.g., streets, residential yards, etc). However, it must be stressed that there is no direct biological evidence that one group of fecal bacteria (namely, fecal coliforms and *E. coli*) survive in sewer sediments or drainage channels, whereas another (*Enterococci*) survive as deposits on the surface of urban landscapes. Further research is needed to test this hypothesis and more generally clarify the relationship between the watershed-scale response of fecal indicator bacteria to storms as manifest by the power law relationship between pollutant loading and flow and the local-scale processes responsible for mobilizing contaminants during periods of intense rain. It should also be noted that the simple scaling model presented here does not explicitly take into account fate and transport processes, such as bacterial die-off. The relative utility of watershed-scale pollutant fate and transport models, on one hand, and simple scaling models, on the other hand, is also an interesting topic for future research.

## Management Implications

**Question:** *What are the management implications of the field data and modeling results presented in this study?*

**Answer:** *Dry and wet weather runoff is a significant source of fecal indicator bacteria; hence, efforts to reduce the flow of untreated runoff to sensitive receiving water bodies are warranted. In the case of fecal pollution shed from the Talbert watershed and its impact on surf zone water quality at Huntington Beach, diversion of dry weather runoff to the sanitary sewer system is likely to reduce the health risk to recreational bathers during high-use summer time periods. However, significant reduction of fecal pollution shed from this watershed on a year-round basis will require the augmentation of dry weather diversions with alternative approaches (e.g., creating freshwater wetland treatment systems to remove contaminants near their source) and implementing watershed management strategies that minimize the loading of sediment-associated pollutants during storms.*

Urban runoff is increasingly recognized as a significant cause of coastal water quality impairment (*18, 27–30*). One approach for addressing this problem is to capture and treat urban runoff before it reaches the ocean. This strategy was adopted in the Talbert watershed after the summer of 1999 when a significant stretch, at one point encompassing 5 km of Huntington State Beach, was closed to the public due to elevated concentrations of fecal indicator bacteria in the surf zone. On the basis of the data presented above, the efficacy of this diversion program is mixed. On one hand, the diversions are effective at reducing the flow of fecal indicator bacteria, and presumably other contaminants associated with urban runoff, into the ocean during dry weather periods. The evidence includes the following: (i) The concentration of fecal indicator bacteria is extraordinarily high in sources of urban runoff, particularly residential runoff, and at collection points for urban runoff (i.e., forebays) (sub-drainage studies A–C; curb and gutter study; channel and forebay study). (ii) Fecal indicator bacteria concentrations increased in runoff from 1999 to 2001 as progressively more dry weather runoff in the Talbert watershed was diverted, while fecal indicator bacteria concentrations at the coastal outlet did not change significantly (sub-drainage studies A–C). (iii) The concentration of TC, and to a lesser extent EC and ENT, was generally higher upstream and lower downstream, of diversion dams in the Talbert and Greenville–Banning channels (channel diversion study). On the other hand, when the entire 6-month study is considered, the vast majority (>99%) of fecal indicator bacteria from the Flounder and Yorktown sub-drainages were shed during rainstorms when diversions were not operating (channel and forebay study). Hence, while diversions appear to reduce the flow of fecal indicator bacteria to the ocean during dry weather periods when the majority of the people are at the beach, they capture a remarkably small percentage (<1%) of the fecal indicator bacteria shed on a year-round basis.

The human health implication of this result is difficult to ascertain without further investigation. Beach usage is generally light during storms, when the loading of fecal indicator bacteria is highest. Hence, one might conclude that the intense loading of fecal indicator bacteria during storms poses little health threat. On the other hand, the delivery of contaminated sediments and particles to the nearshore during storms could lead to chronic contamination of beach areas located near runoff outlets (*31–34*). Indeed it is interesting to note that elevated concentrations of fecal indicator bacteria in the surf zone at Huntington State Beach began in the summer of 1998 (*5*), following an unusually wet El Nino winter in southern California. The delivery of contaminated sediment to the coastal zone during storms may also disrupt fragile nearshore ecosystems by contributing excess toxicity (*28, 35*). If erosion of sediments is driving the loading of fecal indicator bacteria from urban watersheds, then regular removal of contaminated sediments accumulating in the storm sewer system might be an appropriate management strategy. The creation of distributed wetland treatment systems, in which contaminants in urban runoff are removed near their source, might also prove useful for reducing downstream impacts.

## Acknowledgments

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# Identifying Pollutant Sources in Tidally Mixed Systems: Case Study of Fecal Indicator Bacteria from Marinas in Newport Bay, Southern California

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This study investigates the contribution of several marinas to fecal indicator bacteria impairment in Newport Bay, a regionally important tidal embayment in southern California. Three different fecal indicator bacteria groups were assayed, including total coliform, *Escherichia coli*, and enterococci bacteria, all measured using the IDEXX Colilert and Enterolert system. To document temporal variability in the fecal indicator bacteria signal, water column samples ($n = 4132$) were collected from two marinas over time scales ranging from hours to months. To document spatial variability of the fecal indicator bacteria signal, water column and sediment samples were collected from a number of sites ($n = 11$ to 36, depending on the study) in and around the two marinas, over spatial scales ranging from meters to kilometers. To identify the dominant temporal and spatial patterns in these data a statistical approach—Empirical Orthogonal Function analysis—was utilized. Finally, to clarify the transport pathways responsible for the observed temporal and spatial patterns, fecal indicator bacteria data were compared to simultaneous measurements of tidal flow, temperature, and salinity. The results of this field effort collectively implicate runoff—both dry weather runoff at sampling sites located near some storm drains and wet weather runoff at all sites—as a primary source of fecal indicator bacteria in the water column and subtidal sediments. The results and analysis presented here reinforce the growing body of evidence that management of fecal indicator bacteria impairment in the coastal waters of southern California will require developing long-term strategies for treating nonpoint sources of both dry weather and stormwater runoff.

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## 1. Introduction

The development of total maximum daily load (TMDL) management plans for impaired receiving waters requires, at a minimum, knowledge of the location and magnitude of pollutant sources potentially responsible for the impairment. While this information may be obvious in cases where pollutant point sources are clearly delineated (eg., sewer outfalls), in many cases the causes of impairment, and associated pollutant transport pathways, are either unknown or poorly constrained. In this study we develop and test a field-based approach for addressing the latter situation in tidally mixed systems such as marinas, embayments, estuaries, and tidal saltwater marshes. Identification of pollution sources is particularly challenging in tidally mixed systems because the flow field is constantly changing both direction and magnitude with the tides. For such systems coastal managers are often confronted with the following fundamental but difficult-to-answer question: Is the majority of pollution coming from a specific component of the system (e.g., a particular geographical region)? At a more fundamental level, this question can be restated as follows: What are the dominant spatial and temporal patterns associated with the pollutant of concern, and how are these patterns related to specific pollutant sources and transport pathways?

Here we show that these questions can be answered by implementing a carefully designed field monitoring program, and analyzing the resulting multidimensional data set using a statistical technique called Empirical Orthogonal Function (EOF) analysis. We use this approach to determine if nonpoint sources of fecal pollution originating in two recreational marinas (e.g., from illicit vessel discharges, urban runoff drains, vessel pump-out facilities) are the primary source of fecal indicator bacteria impairment in Newport Bay, a regionally important tidal embayment in southern California.

The EOF approach described here is complementary to other statistical methods for analyzing coastal water quality time series data, such as analysis of variance, or ANOVAs; see Boehm and Weisberg (*1*) for an excellent example of the latter relative to fecal indicator bacteria measurements at beaches in southern California. ANOVA is a statistical approach for quantitatively comparing the mean and variance of different groups of data (e.g., fecal indicator bacteria measurements collected from the surf zone during spring tides versus those collected during neap tides in the example presented by Boehm and Weisberg). The EOF approach described here, on the other hand, identifies the dominant temporal patterns (or "modes") in a spatially distributed data set, and provides a measure (or "loading") of a mode's strength at each sampling site. Put another way, EOF analysis is an unbiased statistical approach for identifying the dominant temporal patterns in a time series data set, and how these temporal patterns are distributed spatially—precisely the information needed to answer the questions posed above.

The data collection and analysis described in this paper is complementary to other published methods for identifying sources of fecal pollution in coastal systems, including source-tracking methodologies that aim to identify the primary host (e.g., human, bovine, avian, etc.) of fecal indicator pollution (*2*), the identification of high-risk and low-risk sites based on the co-variation of multiple fecal indicator organisms (*3–5*), and process studies that couple fate and transport studies with fecal indicator occurrence patterns (*6–14*). A theme that emerges from many of these studies is that fecal indicator

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**TABLE 1. Timing and General Features of the Five Marina Studies**

| study[a] | timing | antecedent dry weather period (days) | number of sites |
|---|---|---|---|
| BYB I | 07/26 16:00 ≤ 07/29 04:00, 2002 | 67 | 11 |
| Dunes I | 09/20 16:00 ≤ 09/23 04:00, 2002 | 123 | 11 |
| BYB II | 11/22 16:00 ≤ 11/25 04:00, 2002 | 6 | 27 |
| Dunes II | 04/18 16:00 ≤ 04/21 01:00, 2003 | 2 | 36 |
| Dunes III | 08/29 16:00 ≤ 09/01 01:00, 2003 | 29 | 24 |

[a] BYB, Balboa Yacht Basin marina; Dunes, Dunes marina.

174 boat slips, Dunes has 450 boat slips), shape, and, presumably, tidal flushing characteristics (see Figure S1 for aerial photos of the BYB and Dunes marinas). During the set of field experiments described here the tide range (i.e., the difference between the daily high-high and low-low tides) varied from 1.7 to 2.3 m. Estimates for the flushing time scales of Upper and Lower Newport Bay vary from days to months, depending on the region of interest (e.g., Upper Bay vs Lower Bay) and assumptions employed in the flushing calculation (*23, 24*).

**Water Column Sampling and Analysis.** Table 1 summarizes key features of the experimental design employed in the five studies. Altogether, 4132 water samples were collected from the BYB and Dunes marinas over a 14-month period of time, from July 2002 through September 2003. All five studies were conducted during dry weather periods; however, the elapsed time from the last storm (or antecedent dry period) varied from 2 days (for the Dunes II study) to 123 days (for the Dunes I study). All five studies had similar experimental designs, although the number of samples collected, and the spatial distribution of sampling sites, varied. Sampling sites were divided into four categories based on their location: (1) marina samples, collected from the marina being studied; (2) channel samples, collected from the channel adjacent to the marina; (3) storm drain impacted samples, collected from the marina or channel near storm drain outlets; and (4) lagoon samples, collected during the Dunes II study from a lagoon near the Dunes marina (see Figure 1).

The number of sites sampled, and the sampling frequency, were arrived at after weighing several different objectives including the following. (1) To assess the reproducibility of the sample collection and analysis methods, duplicates were collected for 10% of all samples. (2) To capture tidal and day/night (diurnal) changes in the fecal indicator bacteria signal, water samples were collected every 3 h, 24 h per day, for the duration of each 2.5 day study period. (3) To assess vertical stratification of fecal indicator bacteria in the water column, paired water samples were collected from each site, one from the surface of the water column and another from 1 m below the surface. (4) To maximize the possibility of detecting illicit discharges from vessels inside the marinas, studies were conducted over the course of a weekend (from Friday afternoon through Monday morning) when boat usage was significant. Several of the studies were conducted during holiday periods (the Dunes III study was conducted over Labor Day weekend, and the Dunes II study was conducted over Easter Sunday).

All samples were transported a short distance to UCI (denoted by the anteater in Figure 1) where they were analyzed for fecal indicator bacteria—including total coliform (TC), *Escherichia coli* (EC, a sub-group of fecal coliform, FC), and enterococci bacteria (ENT)—using defined substrate tests known commercially as Colilert and Enterolert, implemented in a 97-well quantitray format. This particular test was utilized because it is quantitative, relatively inexpensive, and not labor intensive. The last feature made possible the processing of a large number of samples on a 24 h per day basis. The Colilert method, when implemented for marine waters, can yield false TC positives (*25–27*). However, the frequency of false TC positives does not appear to be significant relative to the background noise associated with fecal indicator assays (*27*). Because we utilize only the Colilert and Enterolert methods in this study (i.e., we are not mixing results from different assay methods) the results reported here are internally comparable. All water samples were also analyzed for salinity, turbidity, and pH using methods described elsewhere (*28*). Details of the water column sampling, including the logic used in selecting the sampling sites, can be found in the Supporting Information for this paper.

**Sediment Sampling and Analysis.** During the Dunes II and Dunes III studies, two subtidal sediment samples were collected once daily from the same set of sites where water samples were collected every 3 h. In all, 115 sediment samples were collected and analyzed for fecal indicator bacteria, including 55 and 60 during the Dunes II and Dunes III studies, respectively. Immediately prior to sampling the sediment, a 500-mL water sample was collected from the bottom of the water column (just above the bed) using a custom ball-valve sampling system affixed to a telescoping pole. The water samples were handled and analyzed using the procedures described above.

Sediment was collected in two 50-mL conical tubes (Fischer Scientific, Pittsburgh, PA) affixed to the end of a telescoping pole. The pole was lowered over the side of a small boat, and the conical tube was forced into the bottom sediments to a depth of approximately 10 cm. The pole was then raised, and if the conical tube contained sediments it was capped and immediately placed on ice. If the conical tube did not contain sediments (e.g., due to wash-out of the sediments as the tube was raised through the water column), the entire procedure was repeated. This method worked well at most sites because of the soft (i.e., fine grained and organic rich) nature of bottom sediments in the Bay. Sediment samples were analyzed at UCI using a procedure similar to the one described by Craig et al. (*29*). Specifically, sediment (25 g wet weight) was added to a 500-mL centrifuge bottle (Kendro Laboratories, Asheville, NC), resuspended in 75 mL of 0.1% Peptone (Difco, Sparks, MD), hand shaken for 1 min, and then centrifuged at 500 rpm for 10 min at 4–10 °C using a GS 3 rotor in a Sorvall RC28S Hybrid centrifuge (Dupont, Willmington, DE). The centrifuge bottles were recovered, and 10 mL of the supernatant was collected and analyzed for fecal indicator bacteria using the Colilert and Enterolert defined substrate tests, as described above. The sediment fecal indicator bacteria concentration $C_s$ was calculated from the following formula:

$$C_s = \frac{C_t 75\text{mL}}{W_s r} \times 100 \text{ (units of most probable number (MPN)/100 g dry sediment)} \quad (1)$$

where $C_t$ is the concentration of fecal indicator bacteria measured in the 10 mL of supernatant, $W_s$ is the wet weight (in grams) of sediment resuspended in the 0.1% peptone, and $r$ is the dry-to-wet weight ratio for the sediment. To compute $r$, approximately 2 g of wet sediment from each sediment sample was weighed out, dried overnight in an oven at 110 °C, and re-weighed.

**Current Meter Deployment.** To characterize the predominant tidal flow in the BYB and Dunes marina study areas, a multidirectional current meter with an integrated pressure transducer, thermister, and conductivity meter (S4, InterOcean Scientific) was deployed coincident with the BYB and Dunes sampling periods, with the exception of the Dunes III study for which the S4 instrument was not available. The S4 was anchored by Orange County Sheriff Harbor Patrol

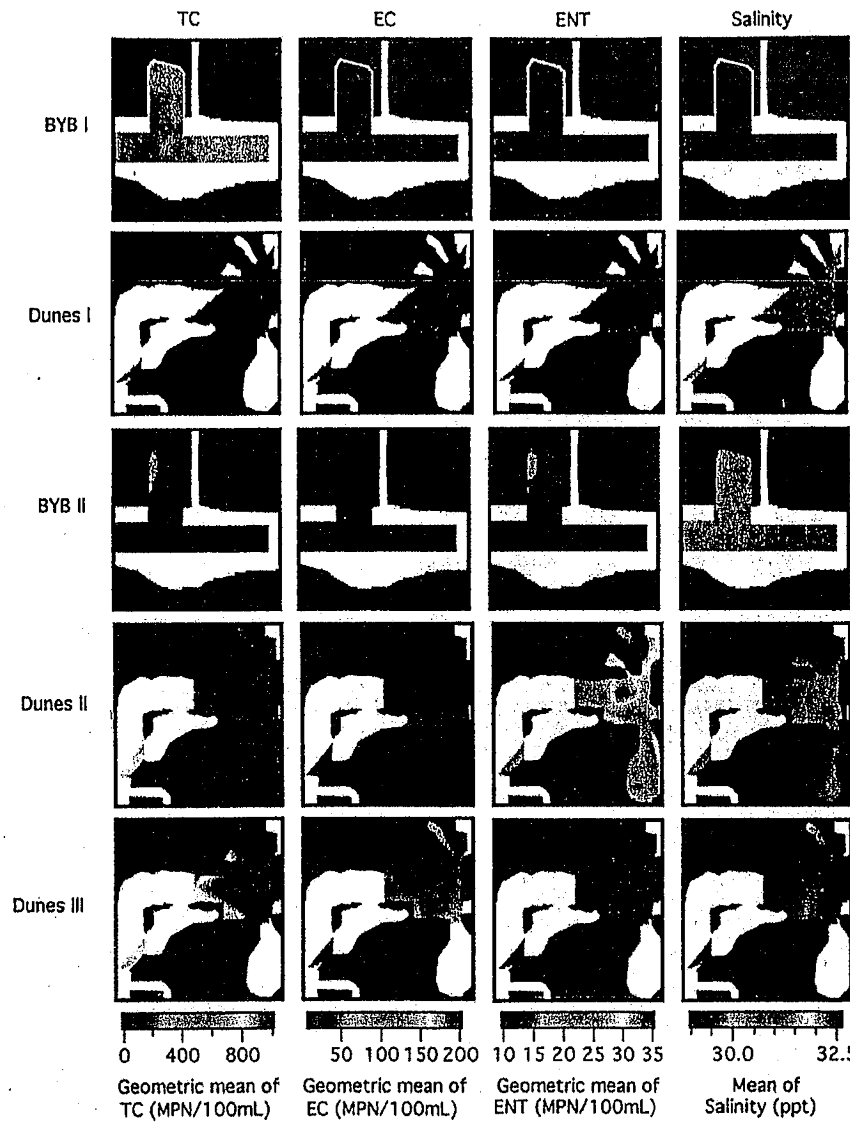


**FIGURE 3. Geometric mean of fecal indicator bacteria and mean salinity measured during the five marina studies.**

the water level data measured by the S4 instrument have a mixed-tide character; i.e., there are four distinct high and low tides per day, including higher-high, lower-high, higher-low, and lower-low tides. During the Dunes I study, the higher-high and lower-high tides are about the same, as are the higher-low and lower-low tides.

Currents recorded by the S4 instrument are strongly forced by the tides, with inland-directed flow coincident with rising tides (positive vertical velocity) and oceanward-directed flow coincident with falling tides (negative vertical velocity). Because of the sinuous geography of Newport Bay, inland-directed flow manifests as westward flow at the BYB site and eastward flow at the Dunes site. The peak velocities recorded by the S4 are approximately 10 and 50 cm/s in the channels outside of the BYB and Dunes marinas, respectively. When averaged over all flood and ebb tides, the absolute magnitude of the tidal velocities are in the range of 4−5 and 17−22 cm/s for the BYB and Dunes studies, respectively.

Temperature and salinity recorded by the S4 instrument in the channel outside of the Dunes marina exhibit tidal cycling, with salinity increasing (decreasing) and temperature decreasing (increasing) during rising (falling) tides (upper right and lower right panels, Figure 2). Tidal cycling of temperature and salinity is not evident in the channel outside of the BYB marina during the BYB I study (upper left panel, Figure 2), although temperature and salinity do exhibit some tidal (diurnal) cycling in the BYB II study (lower-left panel). During the BYB I study, temperature and salinity changed slowly over the two-day sampling period, perhaps reflecting the slow intrusion of warmer and lower salinity water from Upper Bay. Overall, these data reveal that tidal currents strongly influence heat and mass transport in the channel outside of the Dunes marina; the influence of tidal currents is less obvious in the channel outside of the BYB marina. More generally, the oscillating nature of the currents measured here, in which the direction of flow reverses every ca. 6 h, implies that water quality impairment at the two marinas can be affected by a myriad of potential pollutant sources located within, inland, and oceanward of the BYB and Dunes sites.

## 4. Observations of Fecal Indicator Pollution in the Water Column

**Vertical Stratification.** For all practical purposes, fecal indicator bacteria pollution in Newport Bay is mixed down to a depth of at least 1 m (Table S1). In the two cases where

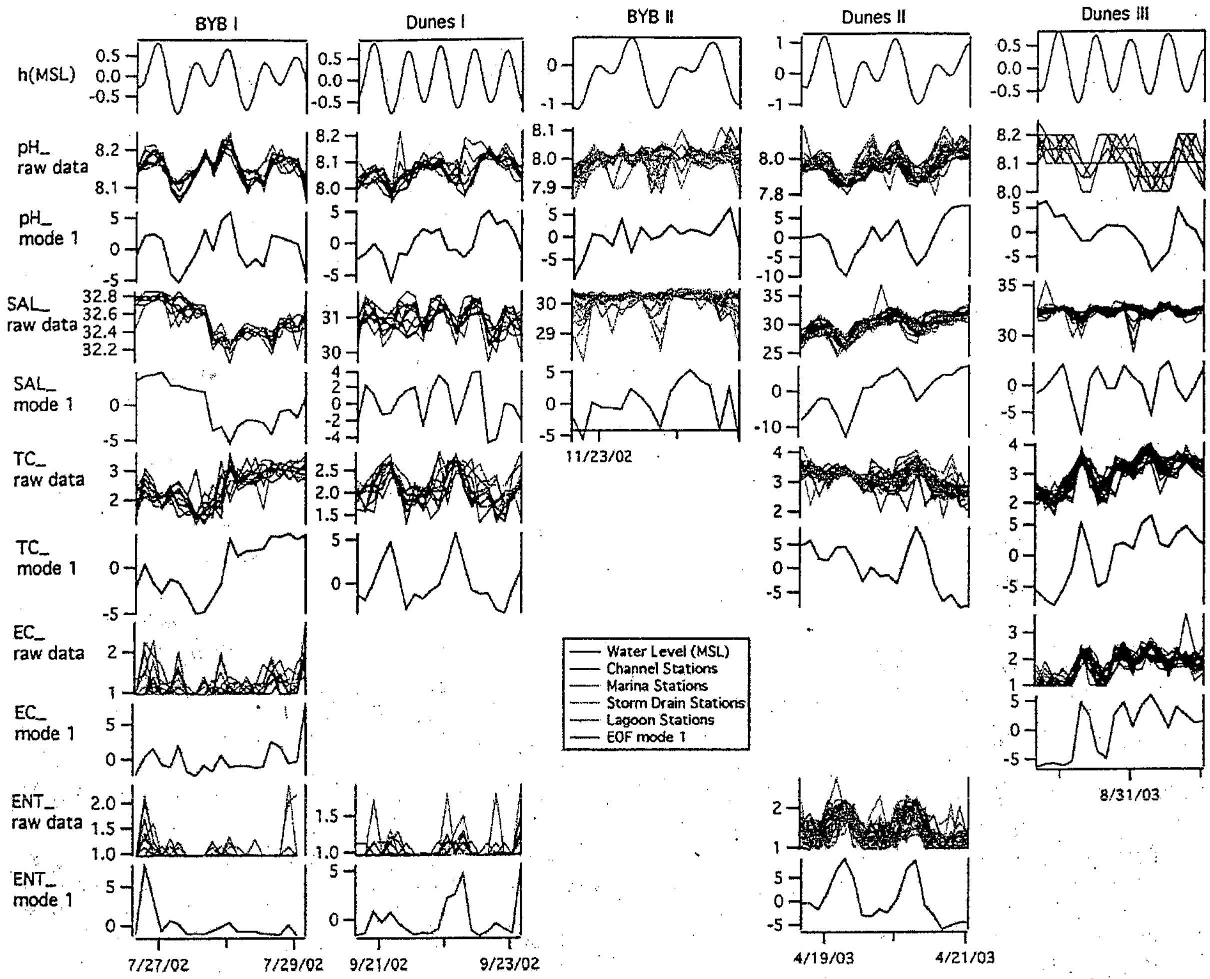


**FIGURE 5. Time series plots of EOF modes calculated from physical (pH, salinity) and fecal indicator bacteria data; only EOF modes for which the first eigenvalue is approximately 50% (or more) are shown in the figure. The black curves represent measured (or computed in the case of Dunes III study) water level. The red, blue, and green curves represent the raw pH, salinity, and log-transformed fecal indicator bacteria data (designated pH, SAL, TC, EC, and ENT). The purple line represent the first EOF mode computed from the de-meaned pH (pH_mode1), salinity (SAL_mode1), and log-transformed TC (TC_mode1), EC (EC_mode1), and ENT (ENT_mode1) data.**

including the following: (1) storm drain sites during the BYB II study (third row of panels, Figure 4), and (2) TC concentrations measured at all sites during the BYB I and Dunes III studies (first and last row of panels, Figure 4).

While the negative correlation between fecal indicator bacteria and salinity—observed at many sites in both the BYB and Dunes field areas—is consistent with a runoff source for these organisms, this negative correlation could also be attributed to more rapid die-off of fecal indicator bacteria with increasing salinity (*36*). Indeed, across all five studies (i.e., BYB I, Dunes I, BYB II, Dunes II, and Dunes III) the negative correlation between salinity and fecal indicator bacteria is most pronounced for TC ($-0.87 < Sp < 0.20$), intermediate for ENT ($-0.69 < Sp < 0.35$), and weakest for EC ($-0.53 < Sp < -0.33$) ($p \leq 0.05$). The pronounced negative correlation between salinity and TC is consistent with the known sensitivity of this fecal indicator bacteria group to high (i.e., near ocean) salinity (*37*).

Finally, we note that there were no consistent relationships between the concentration of fecal indicator bacteria and turbidity (Figure S3, Supporting Information). During the Dunes II study, TC and turbidity were positively correlated ($0.33 < Sp < 0.63$, $p \leq 0.05$) at many sites ($n = 23$), whereas EC and ENT were positively correlated with turbidity ($0.35 < Sp < 0.69$, $p \leq 0.05$) at fewer sites ($n = 8$ and 10 for EC and ENT, respectively). During the other studies (i.e., BYB I, BYB II, Dunes I, and Dunes III) relatively few sites exhibited a significant (at the $p = 0.05$ level) correlation between turbidity and the concentration of fecal indicator bacteria.

## 5. EOF Analysis of Water Column Data

**EOF Modes.** As mentioned in the Introduction, the goal of the EOF approach is to identify the dominant temporal patterns (referred to here as "modes") in time series data, and then to quantitatively determine how these modes are distributed spatially, by examining the spatial distribution of "loadings" associated with each mode. EOF analyses was carried out for the complete set of analytes measured in the five different water column studies (i.e., BYB I, Dunes I, BYB II, Dunes II, and Dunes III). In general, there are as many modes as there are sampling stations, but most of the higher-order modes capture very little variance in the original data set. The modes are ordered according to the percentage of variance captured by each. The first mode captures the most data variance, the second mode captures the next most variance, and so on. Importantly, the magnitude of the eigenvalue associated with each mode, when multiplied by a factor of 100, indicates the percentage of data variance captured by each mode. The EOF eigenvalues computed from the time series measurements of pH, salinity,

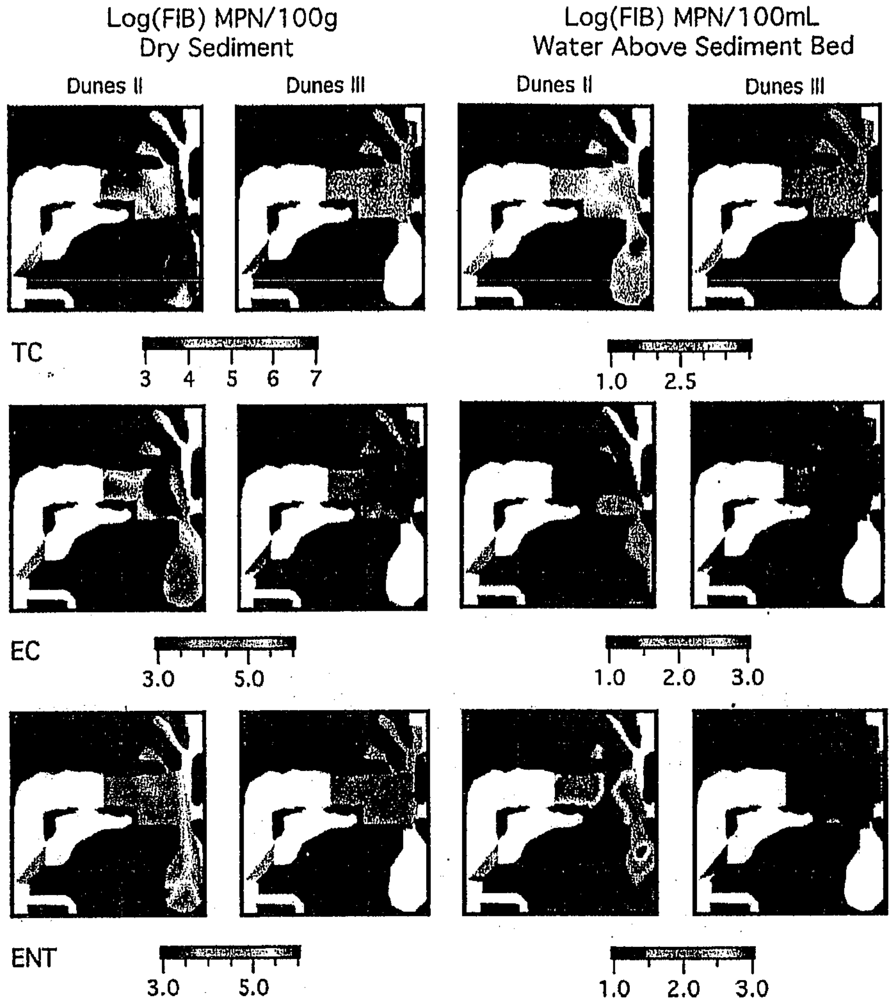


**FIGURE 7. Spatial distribution of fecal indicator bacteria in the sediment during Dunes II (first column) and Dunes III (second column) studies, and in the water just above the bed sediment during the Dunes II (third column) and Dunes III (fourth column) studies.**

result implies that the temporal variability captured by the first EOF mode is relatively homogeneous across all sampling sites; i.e., if the concentrations are rising in one part of the sampling grid, they are rising in the rest of the grid as well.

## 6. Observations of Fecal Indicator Bacteria in the Sediment

The concentration of fecal indicator bacteria in the sediment exhibits significant study-to-study variability (at least for the two studies represented here), and relatively less site-to-site variability (Figure 7 and Table S3; see also Figure S8). Concentrations of fecal indicator bacteria in the sediment were at least 1 order of magnitude higher during the Dunes II study (geometric means in the range $10^3-10^4$ for TC, $10^1-10^2$ for EC, and $10^2-10^3$ for ENT, all in MPN/100 g of dry sediment), compared to the Dunes III study (geometric means in the range $10^0-10^1$ for TC and EC, and $10^1-10^2$ for ENT, all in MPN/100 g dry sediment) (Figure 7 and Table S3).

In contrast, the concentration of fecal indicator bacteria in the sediment is relatively constant across sites, with slightly higher concentrations of TC, and lower concentrations of EC, in the lagoon sediments during the Dunes II study (first column of panels in Figure 7, Table S3). There are no obvious relationships between the concentration of fecal indicator bacteria measured in the sediments and the concentration of fecal indicator bacteria measured in the water column just above the sediment bed (third and fourth columns of panels in Figure 7, Table S3). In particular, there are many examples where the concentrations of fecal indicator bacteria in the sediment are relatively high, but the concentrations of fecal indicator bacteria in the water above the sediment bed are relatively low; the opposite pattern (i.e., sediment concentrations low, above-bed concentrations high) is also apparent in Figure 7.

## 7. Data Synthesis and Practical Implications

This paper sheds light on the spatial and temporal patterns of fecal indicator bacteria concentrations in the water column and sub-tidal sediments of Newport Bay; and on the sources and transport pathways that give rise to these patterns. Water column concentrations of fecal indicator bacteria exhibit significant temporal variability at multiple time scales, including the following: (1) significant study-to-study variability, with the highest concentrations observed for studies with the shortest antecedent dry period (e.g., Dunes II study); (2) semi-diurnal and diurnal variability, to a greater extent at the Dunes site and to a lesser extent at the BYB site; and (3) low-frequency variability as evidenced by an increase or decrease of fecal indicator bacteria concentrations over the course of multi-day field experiments. The EOF analysis indicates that the variability captured by (2) and (3) is fairly homogeneous across the sampling grids; in other words, if the concentration of fecal indicator bacteria is rising at one site in the grid, it

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# Influence of Climate Change, Tidal Mixing, and Watershed Urbanization on Historical Water Quality in Newport Bay, a Saltwater Wetland and Tidal Embayment in Southern California

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Historical coliform measurements ($n$ = 67 269; 32 years) in Newport Bay, a regionally important saltwater wetland and tidal embayment in southern California, have been compiled and analyzed. Coliform concentrations in Newport Bay decrease along an inland-to-ocean gradient, consistent with the hypothesis that this tidal embayment attenuates fecal pollution from inland sources. Nearly 70% of the variability in the coliform record can be attributed to seasonal and interannual variability in local rainfall, implying that stormwater runoff from the surrounding watershed is a primary source of coliform in Newport Bay. The storm loading rate of coliform from the San Diego Creek watershed—the largest watershed draining into Newport Bay—appears to be unaffected by the dramatic shift away from agricultural land-use that occurred in the watershed over the study period. Further, the peak loading of coliform during storms is larger than can be reasonably attributed to sources of human sewage, suggesting that nonhuman fecal pollution and/or bacterial regrowth contribute to the coliform load. Summer time measurements of coliform exhibit interannual trends, but these trends are site specific, apparently due to within-Bay variability in land-use, inputs of dry-weather runoff, and tidal mixing rates. Overall, these results suggest that efforts to improve water quality in Newport Bay will likely have greater efficacy during dry weather summer periods. Water quality during winter storms, on the other hand, appears to be dominated by factors outside of local management control; namely, virtually unlimited nonhuman sources of coliform in the watershed and global climate patterns, such as the El Nino Southern Oscillation, that modulate rainfall and stormwater runoff in southern California.

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## Introduction

Urbanization of the southern California coastline has nearly eliminated what was historically an extensive network of tidal saltwater wetlands (*1*). Of the 29 tidal saltwater wetlands that remain, nearly all have been altered in some way by human activity and many are completely reconstructed systems (*2*). As human activities continue to transform tidal saltwater wetlands and their surrounding watersheds in southern California, coastal managers are faced with developing strategies to minimize, or perhaps even reverse, the negative effects of urbanization on these key ecosystems. However, forecasting the response of a tidal saltwater wetland to specific management decisions (e.g., the building of a housing development in the surrounding watershed) is made difficult by the many physical and biological feedback loops that characterize such systems (*3, 4*). Furthermore, factors completely outside of local control can dominate a wetland's ecological status. For example, global climate change alters the intensity and frequency of rainfall and forest fires in the western United States (*5, 6*). In turn, changes in the frequency and intensity of rainfall and forest fires can alter terrestrial inputs of organic material and sediments into coastal wetlands, with consequent impacts on wetland health and function (*3*).

In this study we compile and analyze 32 years of water quality data—specifically coliform data—measured in Newport Bay, a regionally important embayment and tidal saltwater wetland in southern California. These historical coliform data are interesting for a number of reasons. First, coliform are present at high concentrations in sewage, urban runoff, and agricultural runoff, and hence their presence in coastal wetlands may be an indication of human stress (*1*). Second, while much is known about the utility of freshwater wetlands for removing fecal indicator bacteria and pathogens in urban runoff (*7–13*), to our knowledge there is only one published study that addresses this issue in tidal saltwater wetlands (*14*). The historical data described in this study helps to fill these data gaps. Finally, many wetlands in southern California—including the one we focus on here—are listed by the U.S. EPA as coliform impaired. Hence, insights into the nature of, and causative agents for, temporal and spatial coliform trends are directly relevant to ongoing water quality management programs (e.g., the development of total maximum daily load management plans) (*15*). Another of our articles (*16*) focused on the contribution of marinas to fecal indicator pollution in Newport bay, utilizing data from special studies in which samples were collected at a few marina sites over time scales ranging from hours to months. The focus of this article, on the other hand, is at the scale of the entire wetland, and utilizes historical monitoring data collected at sites scattered throughout Newport Bay and the adjacent surf zone over time scales ranging from months to decades.

## Field Site Description

Newport Bay (hereafter referred to as the Bay) is the second largest embayment in southern California (Figure 1). The Bay can be divided into regions inland and seaward of the Pacific Coast highway bridge (denoted PCH in Figure 1). The lower portion of the Bay (Lower Bay) is a regionally important recreational area, and one of the largest pleasure craft harbors in the United States. The upper region (Upper Bay) is a state ecological reserve and provides refuge, foraging areas, and breeding grounds for a number of threatened and endangered

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and SDC) were selected and TC was adopted as a long-term water quality index. Because the FC data has more gaps, these data were used only for comparison to TC; i.e., trend analyses were not performed on FC data. TC measurements were carried out by OCHCA, using multiple tube fermentation (MTF) (APHA 9221 B) from 1969 to 2001. FC measurements were carried out by OCHCA using MTF (APHA 9221 E.1) from 1985 to 2001. These standard methods yield the concentration of TC and FC in units of most probable number (MPN) per 100 mL of test sample. After 2001 OCHCA changed the analysis method from MTF to membrane filtration (MF). Because results from the MTF and MF methods may not be comparable, we opted not to include the more recent MF data in the analysis reported here. The MTF records of TC are nearly continuous, with the exception of the period 1995–1997 during which sampling at some stations in the Bay was curtailed due to funding constraints (data gaps at each station are summarized in Table S1). Written data records were transcribed into the computer by two students, one of whom called out the test result and observed as the other student entered the number into the computer. TC was also measured in the surf zone along the ocean side of the spit that separates Newport Bay from the ocean (blue stations, Figure 1). These data, which were available for the entire 32-year study period, were obtained either directly from the Orange County Sanitation District, or from data records compiled for a separate study (22). As explained in the Results section, the within-Bay and surf zone data were grouped into four different station categories as follows: Upper Bay, Lower Bay, Western Bay, and Surf Zone. These station categories are designated by different colored symbols in Figure 1.

**Stream Gauge and Rainfall Data.** Daily measurements of surface water flowing into Upper Bay from the SDC and SAD were available for most of the 32-year study period; these data were recorded at the two stream gauge stations indicated by large yellow rectangles in Figure 1 (see Table S1 for data gaps). From 1971 to 1992, stage was measured at SAD using a Stevens Type A-35 analogue recorder driven by a float inside an 18-in. corrugated metal pipe; after 1992 stage was measured using a Stevens A-71 analogue recorder driven by a Fluid Data Balance beam manometer. The latter stage recorder was installed a short distance (approximately 0.4 km) upstream of the older recorder. The gauge station at SDC is equipped with a continuous water stage recorder (Stevens A-71) and ALERT (automated local evaluation in real time) transmitter/data logger. Stream discharge is computed from stage using a Windows Software Hydrologic software program (XStream Measures, Auberry, CA); the Western Hydrological Systems' Surface Water Program (XStream Measures, Auberry, CA) was also used early in the study period. Surface water discharge measurements were carried out bimonthly at SDC using a current meter or a Marsh-McBirney Flo-Mate (Ashtead Technologies, Rochester, NY). Historical rainfall data were measured at a station in Newport Bay (data are available since 1922, designated by NOAA as RNST 88, see blue cross in circle marker in Figure 1). For those periods of time when discharge measurements were not carried out at SDC and/or SAD, discharge values were estimated from rainfall records using the Rational formula (*23*): $Q_s = kAR(t) + b$, where $k$ is the dimensionless runoff coefficient, $A$ is the drainage area, $R(t)$ is the rainfall measurement (in meters/second) at a particular time, and $b$ is the base flow rate in $m^3/s$. These constants were estimated by regressing measured daily discharge against daily rainfall measurements: $kA = 80 \times 10^6 m^2$ (SDC) and $16.1 \times 10^6 m^2$ (SAD), and $b = 0.55 m^3/s$ (SDC) and $0.11 m^3/s$ (SAD). Over the period of time covered by this study (32 years since 1969), rainfall was measured at RNST 88 using a tipping bucket located under a funnel assembly on top of a standpipe structure maintained by County of Orange personnel.

**Modeling of Flushing Time Scales for Newport Bay.** Flushing times in Newport Bay were estimated by simulating flow in the Bay with a two-dimensional hydrodynamic model, RMA2 (*24*), and simulating mass transport in the Bay with a two-dimensional water quality model, RMA4 (*25*). RMA2 is a two-dimensional depth-averaged finite element hydrodynamic numerical model that computes a finite element solution of the Reynolds form of the Navier–Stokes equations for turbulent flows. RMA4 model takes the velocity field from the RMA2 model and solves the depth-integrated transport equations. Figure S2 (Supporting Information) shows the model grid for the Bay. Bay bathymetry was constructed from multiple data sources. Bathymetry for the Lower Bay and the region upstream of the PCH Bridge (see Figure 1) was based on a bathymetric survey conducted by the U.S. Army Corps of Engineers in 1999 and 2001, respectively (*26*). Bathymetry in Western Bay was based on a dredge plan prepared by the City of Newport Beach in 1976 (*27*). Bathymetry in Upper Bay was estimated from a 1999 NOAA Chart (No. 18754). The RMA2 model was run using a mean tide consisting of two daily highs (MHHW and MHW), and two daily lows (MLW and MLLW). The tidal elevations and tidal currents simulated by the RMA2 were then used to drive the water quality model RMA4. To calculate flushing times for the Bay, a numerical experiment was carried out as follows. At time $t = 0$, each within-Bay node was assigned the same initial pollutant concentration, $C = C_0$. Grid nodes on the ocean side of the tidal outlet were assumed to be pollutant free, $C = 0$. The concentration of the pollutant at each within-Bay grid node was then followed over time as contaminated Bay water was replaced with clean ocean water by tidal flushing. An example of one of the resulting concentration–time curves is shown in Figure S3 (Supporting Information). This particular curve was calculated at the numerical gauge shown in Figure S2. Referring to Figure S3, the subtidal simulated concentration decays roughly exponentially with time. Accordingly, the flushing time was taken as the time required for the concentration at a particular site to drop to $e^{-1}$ of the initial concentration (i.e., the time when $C/C_0 = e^{-1}$ or 0.368).

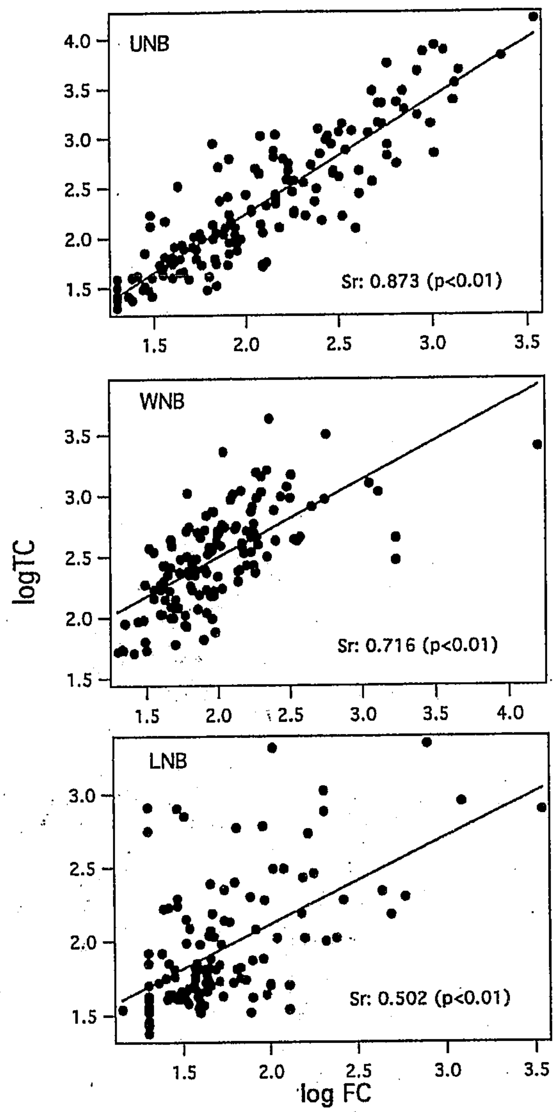
**Frequency Domain Analysis.** To identify periodic patterns in the coliform time series, periodograms were calculated using a fast Fourier transform (FFT) routine numerically implemented in the computer program Matlab (MathWorks, Natick, MA).

**Cumulative Residual Analysis.** Cumulative residuals analysis is a procedure for revealing long-period trends in time series measurements, and involves summing departures of a measurement from the measurement's overall mean. Let $X_j$ represent the value of the measurement in question at the *jth* time point, and let $\bar{X}$ represent the arithmetic mean of $X_j$ over the entire $N$ points in the time series, $\bar{X} = \sum_{i=1}^{N} X_i/N$. The cumulative residual up to the *jth* time point is calculated by summing residual values from the start of the time series to the *jth* time point:

$$C_j = \sum_{i=1}^{j} R_i \qquad (1)$$

where the residual values are departures from the mean at the *ith* time point, $R_i = X_i - \bar{X}$. Cumulative residuals were computed for the following quantities: (1) monthly cumulative rainfall recorded by the rain gauge in Newport Bay; (2) monthly mean volumetric discharge from SDC and SAD; and (3) monthly average log-mean TC concentration measured at four different station categories (Upper Bay, Lower Bay, Western Bay, and Surf Zone).

**Empirical Orthogonal Function (EOF) Analysis.** EOF analysis is an approach for identifying dominant spatial and temporal patterns (or "modes") in time series measurements




**TC vs FC slope:**
**Upper bay 1.1684(+/-) 0.502,**
**Western bay 0.63682(+/-) 0.0626**
**Lower bay 0.59703(+/-) 0.0814**

**FIGURE 2. Cross plot of log transformed total coliform (TC) and fecal coliform (FC) concentrations. The Spearman rank correlations between log TC and log FC are indicated on each panel and the slope of the best-fit line is provided in the key.**

the Pacific Coast Highway have smaller positive JFM anomalies; (3) Stations located in the western portion of Lower Bay have weakly positive to weakly negative JJA anomalies; and (4) finally, surf zone stations have lower log-mean, and smaller (in absolute value) JFM and JJA anomalies. In the analysis presented in this paper, all TC data collected in the Bay and nearby surf zone were therefore grouped into these four station categories, hereafter referred to as Upper Bay, Lower Bay, Western Bay, and Surf Zone stations. Grouping TC data into these four categories facilitated presentation of the time series (by reducing the number of separate time series from 25 to 4), and virtually eliminated data gaps present in the raw water quality data sets. The station category assigned to each sampling station is indicated in Table S1 (Supporting Information) and by the color of sampling stations in Figure 1.

**Spatial Distribution of Flushing Time Scales in Newport Bay.** In tidal embayments such as Newport Bay, the rate at which pollutants locally dissipate due to tidal mixing can vary significantly by location (*35, 36*). This phenomenon can be characterized by plotting the spatial distribution of flushing times, where the latter represent an estimate of the time it takes a conservative pollutant to locally dissipate due to tidal mixing alone (see Materials and Methods Section). Flushing times calculated for the Bay vary from 0 to >30 days (Figure 4). The shortest flushing times occur in regions of the Bay located near the ocean outlet (blue regions in Figure 4). The longest flushing times (ca. 30 days) occur in dead-end regions of the Bay where tidal flow is muted, such as Western Bay and Upper Bay (red regions in Figure 4). Comparing Figures 3 and 4, it is evident that regions of the Bay with the highest 32-year log-mean TC concentrations (and highest standard deviations in the log-transformed TC concentrations) are, in many cases, the same areas with the longest flushing times. However, flushing times alone are not a predictor of the magnitude of local contamination. For example, both Western Bay and Upper Bay have very long tidal flushing time scales (>28 days), yet the 32-year log-mean TC concentration in Upper Bay is approximately 0.6 log units higher than the 32-year log-mean TC concentration in Western Bay.

**Time series of Total Coliform, Rainfall, and Runoff.** Figure 5 presents a 32-year time series of rainfall (blue bars), stream discharge from SAD and SDC (black bars), and monthly log-mean TC concentrations in SAD, SDC, Upper Bay, Western Bay, Lower Bay, and the Surf Zone (red bars). As expected, monthly cumulative rainfall exhibits significant seasonal variability, with most of the rain falling during the winter (JFM) season and little rain falling during the summer (JJA) season. Monthly average discharge records for SAD and SDC also exhibit significant seasonal variability, with peak flow occurring during JFM periods.

Spearman rank correlation between monthly cumulative rainfall and average monthly discharge in SDC and SAD is large (Sp > 0.8) and significant ($p < 0.05$, Figure S4).

TC concentrations measured in SDC and SAD exhibit a weak positive correlation with stream discharge (Sp = 0.34, 0.33, $p < 0.01$), implying that TC in these two creeks is not diluted during periods of high flow (see fourth and fifth panels, Figure 5). Correlations between rainfall and TC concentrations are strong (Sp > 0.6) and significant ($p < 0.05$) in Upper Bay, Lower Bay, and the Surf Zone, but lower for Western Bay (Sp = 0.4, $p < 0.05$) (bottom four panels in Figure 5; see also Table S2 and Figure S4 in Supporting Information). In Upper Bay and SDC, TC concentrations during the summer appear to exhibit interannual (i.e., multi-year) trends, particularly during the second half of the study. For example, summer (JJA) TC concentrations measured in SDC decline during the second half of the study, from a geometric mean of ca. 10 000 MPN/100 mL in 1979 to ca. 1000 MPN/100 mL in 2000 (gray curve in the panel labeled SDC, Figure 5). By way of comparison, the geometric mean standard for TC in California coastal recreational waters is 1000 MPN/100 mL. TC concentrations measured during the summer in Upper Bay exhibit roughly the same interannual trend, peaking in 1979 and declining thereafter (gray curve in panel labeled "Upper Bay stations", Figure 5). Interannual trends at the other sites are more complex and analyzed later in the context of the cumulative residual analysis.

**Frequency Domain Analysis of TC Data.** Periodograms calculated from the 32-year TC data reveal strong annual return periods (12-month periods) in Upper Bay, Lower Bay, and the Surf Zone (Figure 6). These annual return periods—which imply that periods of poor (and good) water quality tend to repeat every 12 months—presumably reflect the role that winter storms play in mobilizing fecal indicator bacteria pollution into the Bay (see discussion above). Periodograms calculated from the Western Bay data, on the other hand,

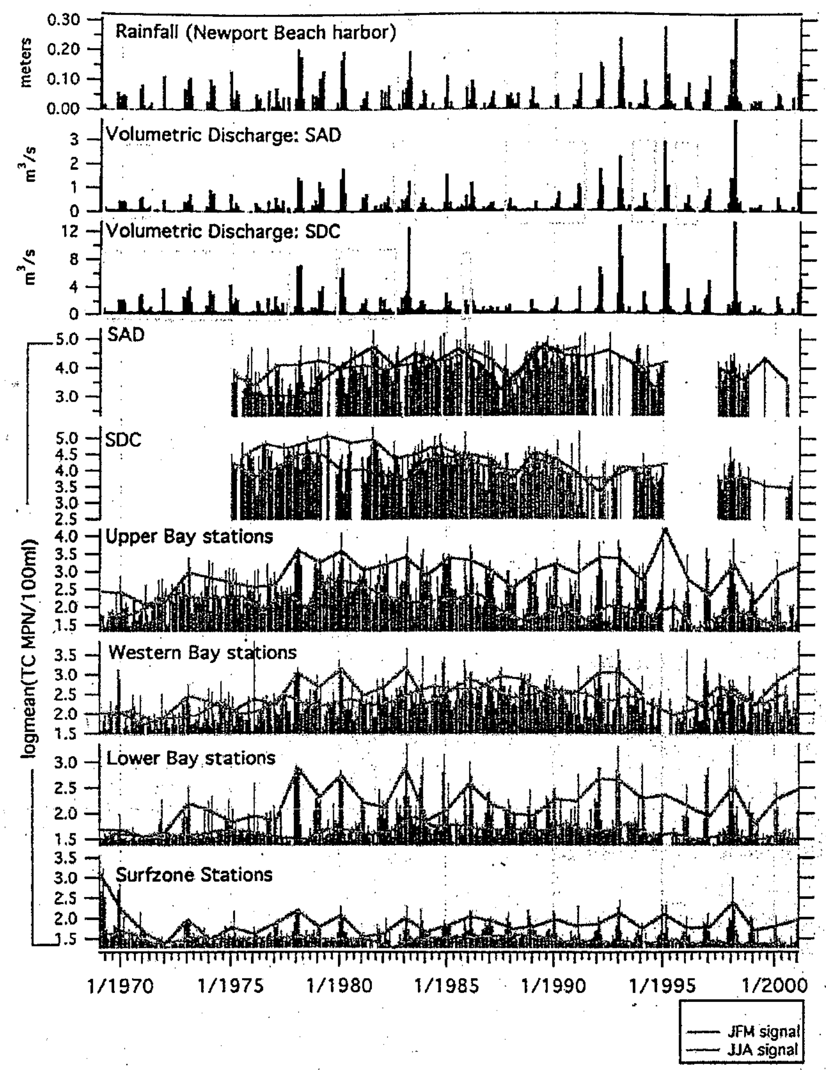



**FIGURE 5. Time series of monthly rainfall totals (blue bars) at Newport Harbor gauge station, volumetric discharge from SAD and SDC (black bars), and monthly TC log means at SAD (Santa Ana Delhi), SDC (San Diego creek), Upper Bay, Western Bay, Lower Bay, and Surf Zone (red bars). Yellow boxes in the discharge time series indicate periods of time when data gaps in the discharge record were filled using the Rational method (see Materials and Methods section). The green and gray solid curves represent the JFM and JJA signals.**

a large percentage of the variance in the de-meaned and normalized TC data set (see Materials and Methods section). The first mode—which accounts for 69% of all the variance in the de-meaned and normalized TC data, as shown in Table S3— is strongly correlated (Sp = 0.7, $p < 0.01$) with total monthly rainfall recorded in the Bay (compare rainfall measurements with Mode 1 curve in Figure 7). In other words, nearly 70% of the variance associated with the de-meaned and normalized TC measurements in the Bay is apparently caused by stormwater runoff. The second mode accounts for approximately 50% of the remaining variance, and is most pronounced in Western Bay (see spatial eigenvalue entries for Western Bay, Table S3). The second mode does not exhibit obvious seasonal patterns before 1985, but after 1985 the second mode is frequently higher in the summer and lower in the winter, precisely opposite the seasonal pattern exhibited by the first mode (third panel in Figure 7).

**Cumulative Residual Analysis of Rainfall, Runoff and Total Coliform.** Cumulative residual analysis is a sensitive method for identifying long-period trends in a time series record (*37*, *38*). Cumulative residuals exhibit an increasing (decreasing) trend when measurements are consistently higher (lower) than average over a sustained period of time (see Materials and Methods section). Cumulative residuals calculated from rainfall records at Newport Beach (top panel, Figure 8) reveal interannual periods of dryer-than-average weather (from the start of the time series in 1969 to 1977, from 1983 to 1991, and from 1998 through the end of the time series in 2001) and interannual periods of wetter-than-average weather (from 1977 to 1983 and from 1991 to 1998). These 5–10 year wet/dry cycles are well-documented for southern California, and correlate with the return period of El Nino Southern Oscillation (ENSO) anomalies which bring wetter than usual winters to this part of the world (*38*).

Long period trends in runoff discharged from the SDC and SAD closely parallel the rainfall trends described above (compare top two panels in Figure 8). Some of this similarity is an artifact of using rainfall records to fill data gaps in the SDC and SAD discharge records (see Materials and Methods and yellow boxes in the second and third panels of Figure 5). Even if these data gaps are excluded, however, the correlation between cumulative residual curves calculated from rainfall and discharge is strong and significant (Sp = 0.96 and 0.61 for SDC and SAD, $p < 0.01$). It is also striking that the cumulative residual curves calculated from the SAD and SDC discharge data are very similar, despite quite

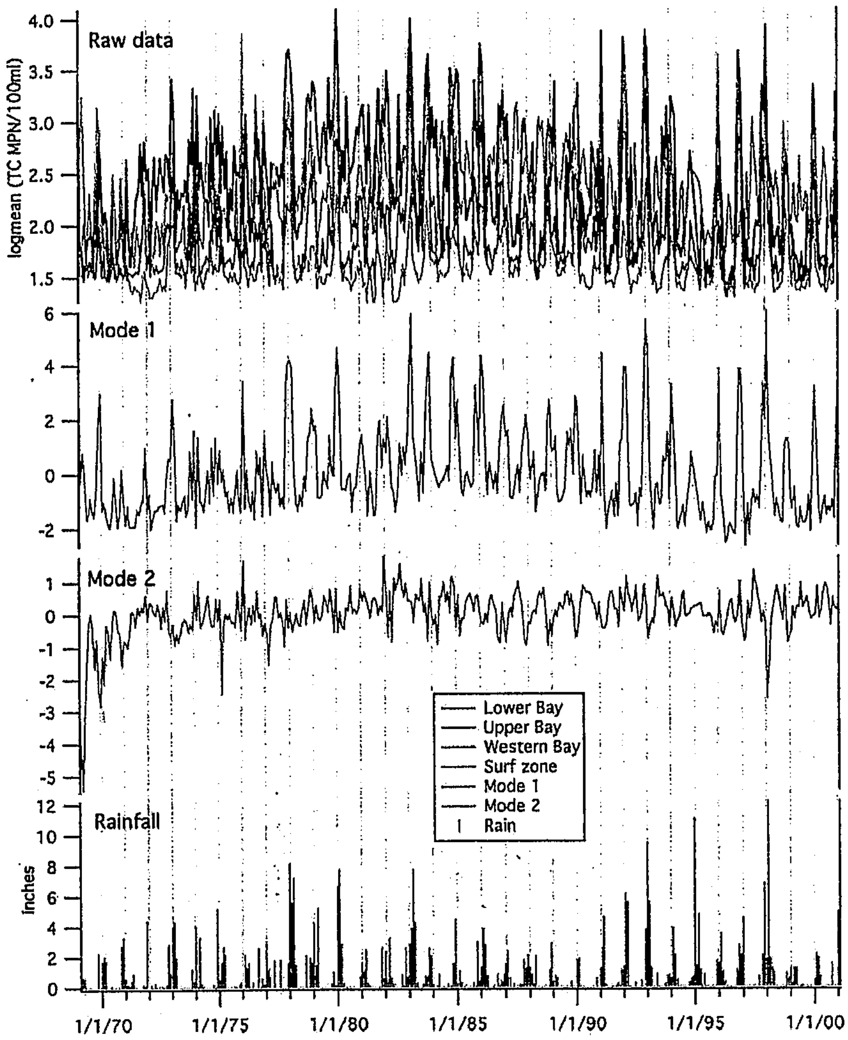



**FIGURE 7. Empirical orthogonal function analysis of log transformed TC data. The top panel displays the raw data. Mode 1 and 2 (gray solid curves) represents temporal Eigenvector 1 and 2. Rainfall is shown in the bottom panel (blue bars).**

a future study by our group, depending on the approach adopted, significantly smaller flushing times (e.g., days instead of months in Upper Bay) can also be obtained (see ref *35* for a good review of flushing time scale calculations). Taken together, these considerations suggest that the absolute magnitude of the flushing time scales plotted in Figure 4 are subject to significant uncertainty, although, on the whole, the within-Bay trends illustrated are likely to be accurate.

It is noteworthy that both the 32-year TC log-mean and JFM TC anomaly decline approaching the Bay's ocean outlet (see Figure 3). This last result suggests that the Bay acts as a natural treatment system for stormwater runoff from the surrounding urban landscape, by tidal dilution, die-off, filtration, sedimentation, or some combination thereof. In an earlier study of a much smaller tidal saltwater wetland called Talbert Marsh (0.1 $km^2$ for Talbert Marsh compared to 8 $km^2$ for Newport Bay), Grant et al. (*14*) concluded that the Talbert marsh is a net source of fecal indicator bacteria to the surrounding surf zone, most likely as a result of bacterial regrowth in the sediment and/or bird droppings deposited on the tidal mudflats from the relatively large number of gulls that visit the marsh on a daily basis. The very different conclusion offered here for Newport Bay—that it reduces rather than increases bacterial concentrations—is likely the result of the very different residence times of water in these two systems. The residence time in Talbert Marsh (ca., 20 min.) is less than the duration of a single flood or ebb tide, implying that any contaminants mobilized into the water column (e.g., from sediment resuspension) (*41*) will quickly flush into the ocean over the course of a single ebb tide. In contrast, the relatively long residence times in the upper reaches of Newport Bay (ca. 30 days according to the flushing time scales indicated in Figure 4) implies that contaminants entering this region of the Bay have much more time to undergo nonconservative transformations—such as die-off, filtration, and sedimentation—before being discharged to the ocean.

Several lines of evidence indicate that human fecal contamination is probably not the sole source of TC pollution in stormwater runoff flowing into the Bay. First, TC concentrations in the SDC creek exhibit a weak positive correlation with volumetric discharge, implying that the concentrations of these fecal indicator bacteria increase with increasing flow. Given that there are a finite number of sources of human sewage in the watershed, markers for human sewage should dilute with increasing stream discharge, contrary to observations. Second, the peak loading rate of FC in SDC—calculated by taking the product of volumetric discharge and FC concentration—is ca. $2 \times 10^{14}$ MPN/day. If all FC in SDC originated from human sewage, this peak-loading rate would correspond to the combined fecal excretions of 100 000 people. This sewage-loading rate of summer time water quality in the Bay is evidenced in several ways. First, cumulative residual analysis reveals that summer (JJA) TC concentrations at the different within-Bay station categories (i.e., Upper Bay, Lower Bay, and Western Bay) exhibit very different interannual trends, and these trends do not parallel interannual trends in rainfall and stormwater runoff. Second, Mode 2 calculated from the EOF analysis is inversely correlated with rainfall, particularly after 1985, and the spatial eigenvalues associated with Mode 2 (see Table S3) indicate that this mode is more pronounced in some regions of the Bay (e.g., Western Bay) and much less pronounced in other regions (e.g., Upper Bay).

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## Supporting Information Available

A brief scaling analysis, land use maps, additional figures, and additional tables. This material is available free of charge via the Internet at http://pubs.acs.org.

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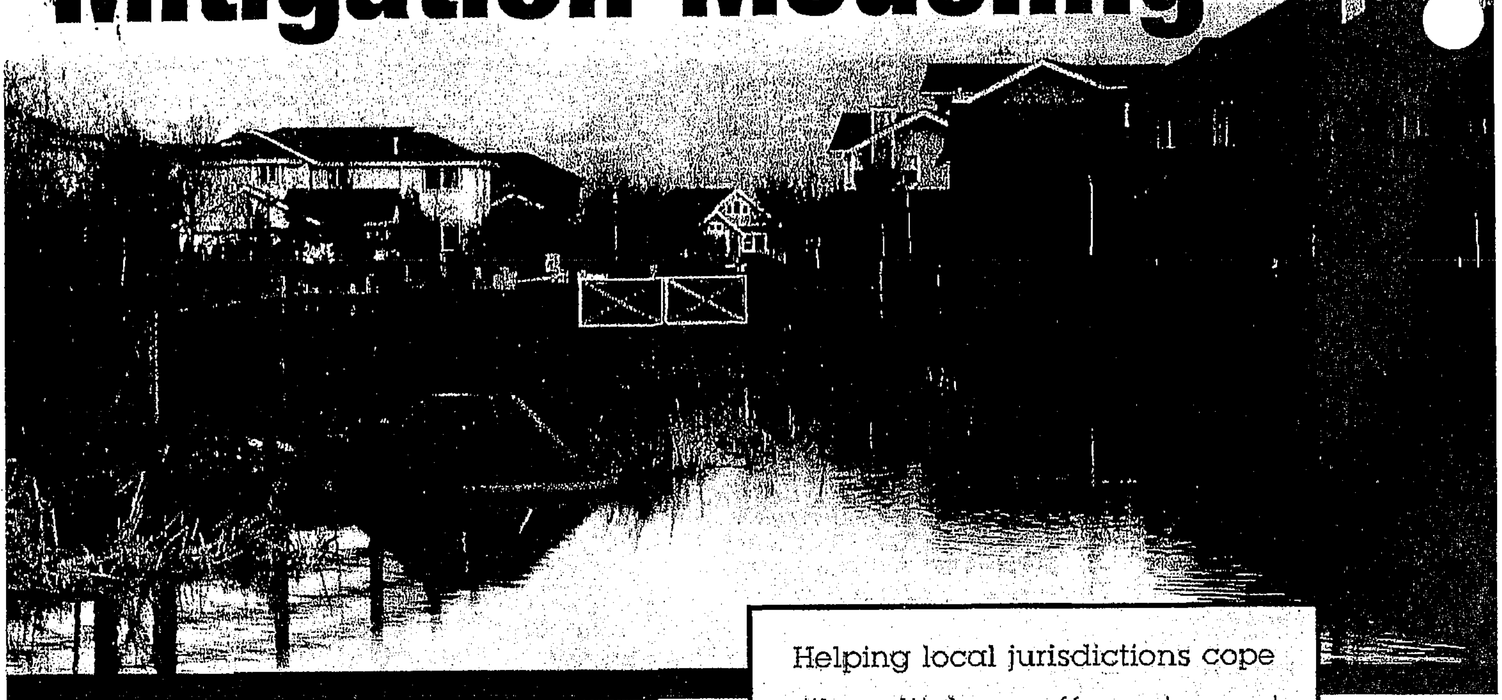
# Flow Duration-Based Stormwater Mitigation Modeling



Helping local jurisdictions cope with multiple runoff requirements

By Douglas Beyerlein

*Implementing improved engineering techniques and drastic changes in where and how land is developed and how people live and move across the land are necessary to achieve the goals in the federal Clean Water Act—to preserve, maintain, and restore the beneficial uses of our nation's waters.*

—Washington State Department of Ecology (2001a)

For the 19 counties of western Washington, stretching from the Columbia River in the south to the Canadian border in the north, stormwater mitigation rules have changed. Today, through National Pollutant Discharge Elimination System (NPDES) permits and certifications under Section 401 of the Clean Water Act, the Washington State Department of Ecology requires flow duration analysis of runoff from new proposed development. Postdevelopment flows cannot exceed predevelopment conditions for flows in the erosive flow range of half the two-year flood to the 50-year flood. Gone are the days of just matching the predevelopment two- and 10-year flood frequencies.

In the state of Washington, the need for new stormwater requirements, standards, and methodologies is the result of state and federal regulations. State regulations under the Growth Management Act and the Water Pollution Control Act as well as under the federal Clean Water Act, Safe Drinking Water Act, and Endangered Species Act call for significant changes in the way we manage urban stormwater runoff. The adoption of a flow duration–based standard and methodology allows us to accomplish these goals.

Similar efforts are beginning in parts of California to meet NPDES municipal separate storm sewer system (MS4) permit requirements as they pertain to hydromodification impacts (changes in runoff peaks and volumes).

Important in meeting the new flow duration–based requirements is the use of low-impact development (LID) approaches to decrease the amount of stormwater runoff generated from land-use changes. These LID approaches can take on many forms, ranging from pervious pavement to roof gardens (green roofs), and they can be incorporated in flow duration–based modeling to determine their effectiveness in reducing stormwater peaks and total volume. This, in turn, reduces the stormwater detention storage required to meet predevelopment runoff conditions.

## Background

The Washington State Department of Ecology realized the difficulty for engineers to meet a flow duration–based standard, a requirement that is part of the 2001 Stormwater Management Manual for Western Washington (Washington State Department of Ecology 2001b). To facilitate the needed flow duration analysis, the Department of Ecology contracted with Aqua Terra Consultants to develop a computer modeling package to model predevelopment and postdevelopment runoff and perform the flow duration analysis. This software package became the Western Washington Hydrology Model (WWHM).

The purpose of the WWHM is to provide a visually oriented interactive tool to optimally size stormwater control facilities (for both water quantity and water quality) to mitigate the stormwater and water-quality impacts of land-use changes on local streams and rivers. The model can also be used to review development plans for compliance with stormwater regulations, promote sustainable development practices, and educate the engineering community and public on the impacts of land-use changes.

The model uses the Washington State Department of Ecology's flow duration standard to prevent erosive flows from increasing with increased runoff from new development. Flow duration is defined as the percent of time flow exceeds a specific value.

Analysis and studies conducted by Booth and Jackson (1997) show that there is a range of stream flows that produces the majority of erosion in western Washington streams. This erosive flow range is from approximately one-half of the two-year flood to the 50-year flood. Modeling work by Beyerlein (1999) demonstrated that standard mitigation methods focusing solely on frequency events, such as the two-year and the 10-year flood, do not address the erosive flow issue and consistently undersize stormwater control facilities. This is because the total volume of stormwater runoff increases with the level or intensity of land development (Figure 1). Single-event flood frequency–based methods (such as SCS curve numbers, the Santa Barbara Urban Hydrograph, and the Rational Method) do not address this problem and consistently undersize stormwater storage requirements (Figure 2). The solution is to use continuous simulation hydrologic modeling.

Thom Hooper of the National Oceanic and Atmospheric Administration (NOAA) Fisheries in Seattle explains the problem from a fisheries perspective: "In western Washington, broad habitat degradation is perhaps the most significant contribution to the decline of wild salmon stocks. Salmon have evolved to habitat conditions dependent on the recruitment of clean gravel and flow of uncontaminated cold fresh water for spawning, egg development, and successful fry emergence. Altered landscapes have adversely affected the delivery of sediment and gravel and significantly altered stream hydrology and water quality. Loss of forest cover, increases in impervious surfaces, and increased drainage networks have had a contributing role. New development and redevelopment should be done in such a way as to prevent further degradation of stream channels. Implementation of the Western Washington Hydrology Model to engineer stormwater abatement measures is a promising tool to help accomplish this."

King County (the Seattle metropolitan area), WA, was first to require flow duration analysis for proposed new development. The King County Runoff Time Series (KCRTS) model is the required continuous simulation methodology under the 1998 King County Surface Water Design Manual (King County 1998) for sizing stormwater detention and infiltration flow control facilities. KCRTS is specific to King County and uses pregenerated HSPF (Hydrological Simulation Program–FORTRAN) runoff time series to perform the flow duration analysis.

Although KCRTS led the way in the use of flow duration analysis to size stormwater detention ponds, its computational limitations and menu-driven interface did not make it a useful tool for flow duration–based stormwater mitigation modeling throughout the 19 counties of western Washington. Recognition of KCRTS's limitations led to the development of the WWHM. Dr. Foroozan Labib of the Department of Ecology's Water Quality Program says that the need for a new tool was evident when "Ecology concluded that to protect stream channels in western Washington from accelerated erosion, it must adopt a flow duration standard for urban stormwater discharges to streams. Achievement of this standard requires

**Figure 1.** Rainfall Distribution, Seattle, WA

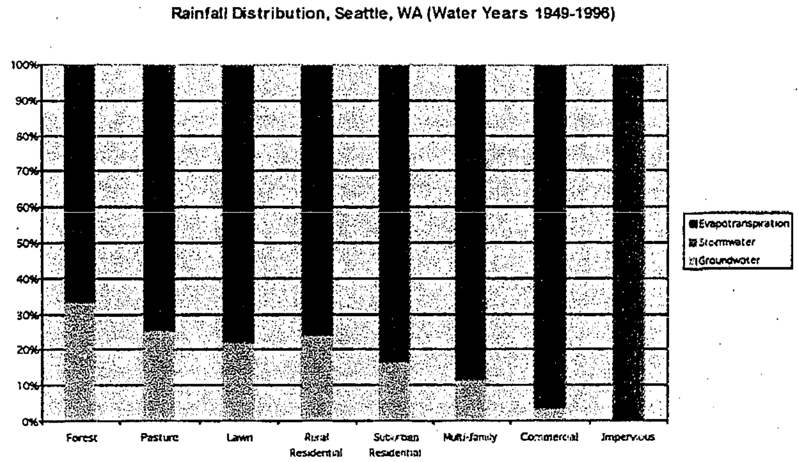
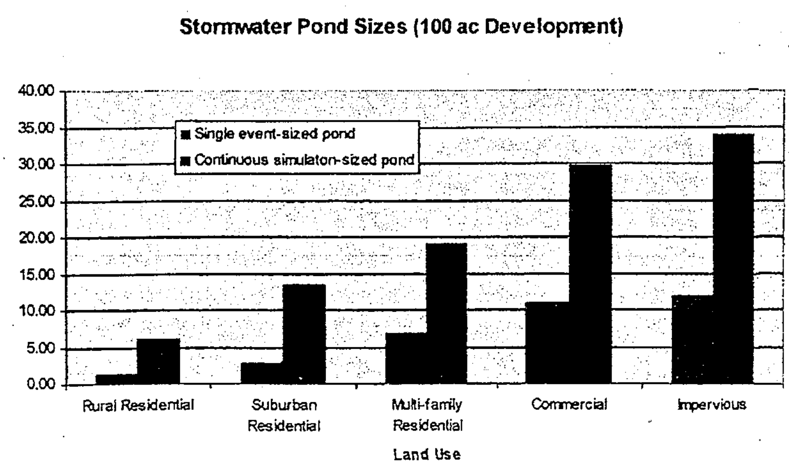



**Figure 2.** Comparison of Single-Event and Continuous Simulation-Sized Ponds



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the use of continuous simulation runoff modeling."

The Department of Ecology's goal was to develop a continuous simulation hydrologic model for western Washington to perform flow duration analysis. The components of this goal included the ability to

- simulate the predevelopment runoff for a user-defined site using HSPF and a long-term meteorological record;
- simulate the postdevelopment runoff based on user-specified development conditions;
- provide runoff time series input to commercial software packages to size stormwater mitigation facilities;
- shield the complexities of HSPF from the general user; and
- allow access to the full capabilities of HSPF for the more advanced user.

WWHM version 1.0, produced in 2001, achieved all of these goals. After this first version was introduced to the engineering and regulatory communities, the Department of Ecology sponsored a series of training workshops throughout western Washington. At the workshops participants had the opportunity to try the software and provide feedback on their initial experiences. Some 300 engineers, planners, and reviewers attended. Feedback was generally positive, although it was widely recognized that the WWHM needed to include the ability to size stormwater ponds without the user having to employ a separate third-party software program, as was the case with version 1.0.

WWHM version 2 (WWHM2) corrected this limitation and added an AutoPond feature that automatically sizes and optimizes a stormwater detention pond to meet flow duration requirements. WWHM2 also added a new user interface, more flexibility in selected predevelopment and postdevelopment land-use conditions, multiple basins and ponds, and water-quality calculations. The user's manual (Washington State Department of Ecology 2003) documents all of the new features and provides detailed directions for all of the options in the model.

WWHM2 workshops were held in the summer of 2003. More than 400 engineers attended the four-hour training sessions. The feedback was overwhelmingly positive. Erik Davido, principal/president of Davido Consulting Group in Seattle, says that "WWHM2 takes a complex model [HSPF] and makes it a quick and useful tool for sizing stormwater ponds."

This strong positive response by the engineering community encouraged the Department of Ecology to fund version 3, which is currently under development.

Jim Scanlin, program manager of the Alameda (California) Countywide Clean Water Program, also found that the WWHM approach to stormwater design would meet his program's NPDES MS4 permit requirements. "Our member agencies initially considered a design storm approach, but as we tracked the progress of studies by the Santa Clara Valley Urban Runoff Pollution Prevention Program, the results pointed to the flow duration approach as the most technically sound way to address the hydromodification management plan permit requirements. Our next concern was finding a way to implement flow duration design that would be practical for the developers and municipal reviewers, which led us to look at adapting the WWHM."

WWHM2 is available free of charge from the Washington State Department of Ecology Web site at www.ecy.wa.gov/programs/wq/stormwater/wwhm_training/wwhm/wwhm_v2/instructions_v2.html. More WWHM2 information is available at www.wwhm2.com/.

## Methodology

The WWHM uses HSPF (Bicknell et al. 2001) as its computational engine. HSPF is the US Geological Survey (USGS) and Environmental Protection Agency continuous simulation hydrology software package, maintained by Aqua Terra Consultants. HSPF, since its introduction in 1980, has become the industry standard for hydrologic modeling.

The HSPF continuous simulation model is preferred over single-event hydrology models because of its ability to compute and keep track of all of the individual components of the hydrologic cycle, including surface runoff, interflow, groundwater, soil moisture, and evapotranspiration. Surface runoff (also known as overland flow) is the first runoff component to reach the stream and is usually the major source of urban flood, as it is generated mainly by impervious surfaces. Interflow travels laterally through the upper soil layers until it reaches a conveyance system (Linsley et al. 1982). Interflow moves more slowly than surface runoff but can still cause flooding problems. Stormwater is the sum of surface runoff and interflow. Groundwater replenishes the aquifer and/or provides base flow to the stream. Evapotranspiration is the sum of evaporation from land surfaces and transpiration from plants. Urbanization decreases groundwater and evapotranspiration and increases stormwater runoff (Figure 1).

The HSPF hydrology parameter values used in the WWHM are based on calibrated watersheds located in western Washington. The USGS Water-Resources Investigations Report 89-4052, Characterization and Simulation of Rainfall-Runoff Relations for Headwater Basins in Western King and Snohomish Counties, Washington (Dinicola 1990), is the source for much of the information. The WWHM values have been checked and validated on numerous other small and large watersheds throughout western Washington. That said, however, Labib notes that "Ecology encourages local governments to obtain locally calibrated parameters to be used in the WWHM for watersheds in their jurisdictions."

The WWHM uses one or more long-term local precipitation gages for each of the 19 counties in western Washington and then scales the precipitation to the user's site using published NOAA rainfall map data.

The WWHM computes stormwater runoff for a site selected by the user. The model runs HSPF in the background to generate 40 or more years of hourly runoff data. Stormwater runoff is computed for both predevelopment and postdevelopment land-use conditions. The WWHM routes the postdevelopment stormwater runoff through a stormwater control facility of the user's choice.

Using the predevelopment peak flood value for each water year, the model computes the predevelopment two- through 100-year flood frequency values. The postdevelopment runoff two- through 100-year flood frequency values are computed from the outlet of the proposed stormwater facility. The model routes the postdevelopment runoff through the stormwater facility. As with the predevelopment peak flow values, the maximum developed flow value for each water year is selected by the model to compute the developed two- through 100-year flood frequency.

The actual flood frequency calculations are made using the federal standard Log Pearson Type III distribution described in Bulletin 17B (United States Water Resources Council 1981). This standard flood frequency distribution is provided in USGS program J407, version 3.9A-P, revised August 9, 1989. The Bulletin 17B algorithms in program J407 are included in the WWHM calculations.

The predevelopment two-year flood frequency value is multiplied by 50% to set the lower limit of the erosive flows. The predevelopment 50-year flood frequency value is the upper limit. Flow duration analysis is conducted for 100 flow levels between the lower erosive zone limit and the upper limit. The model counts the number of hours that predevelopment flows exceed each of the flow levels during the entire more than 40-year simulation period. The model does the same analysis for the postdevelopment mitigated flows.

Using the Department of Ecology flow control standard, there are three criteria by which flow duration values are compared:

1. If the postdevelopment flow duration values exceed any of the predevelopment flow levels between 50% and 100% of the two-year predevelopment peak flow values (100% threshold), the flow control standard has not been met.
2. If the postdevelopment flow duration values exceed any of the predevelopment flow levels between 100% of the two-year and 100% of the 50-year predevelopment peak flow values more than 10% of the time (110% threshold), the flow control standard has not been met.
3. If more than 50% of the flow duration levels exceed the 100% threshold, the flow control standard has not been met.

## Model Input

WWHM input is relatively simple. The user must locate the project site on the appropriate county map (Figure 3). The user can zoom in or out on the map to find the exact location. The WWHM uses this information to select the appropriate precipitation record and multiplier for this location.

**Figure 3.** Project Site Location

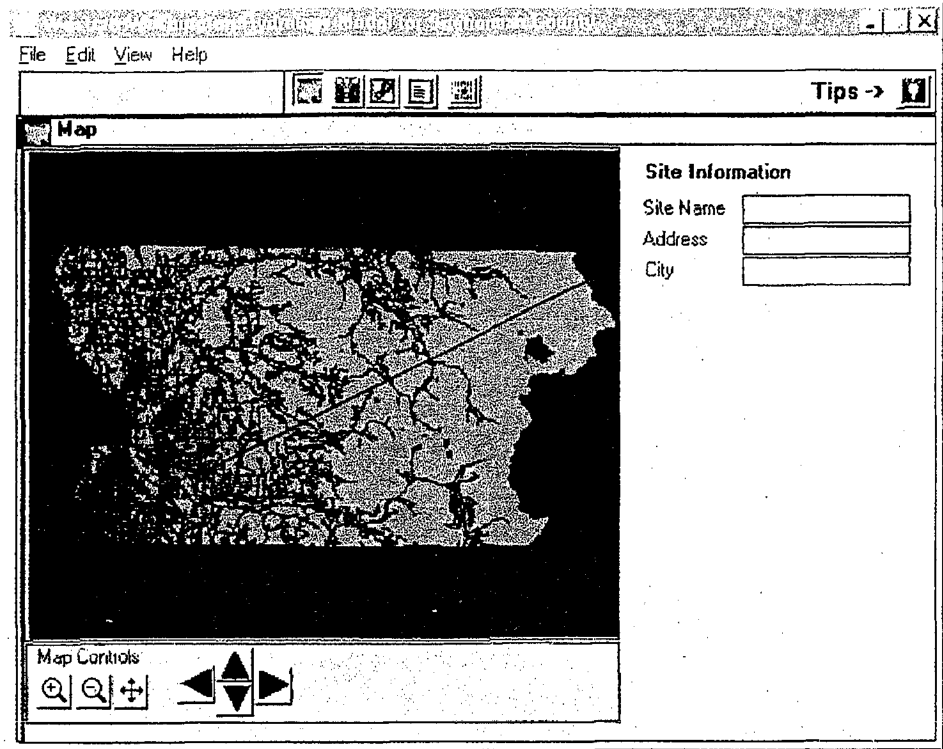
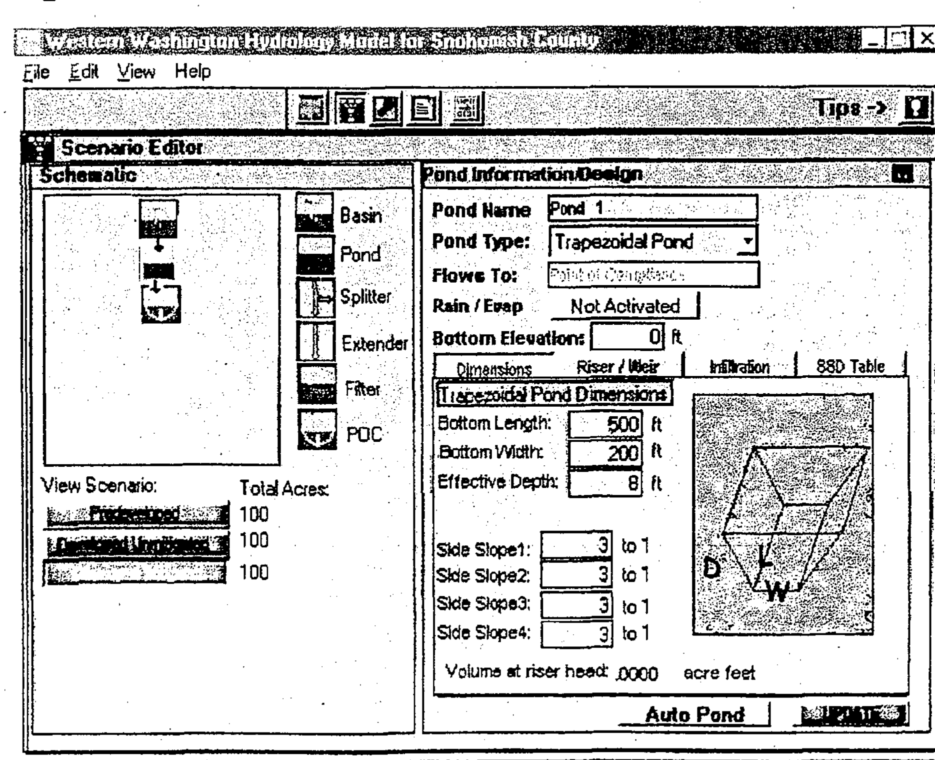



**Figure 4.** Pond Information



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The user then goes to the Scenario Generator screen to specify land-use, vegetation, and soils information. For western Washington, the vegetation categories are forest, pasture, and landscape (lawn). Predevelopment vegetation is assumed to be forest unless the user can document that the natural vegetation for the site was something else (for example, pasture). Western Washington has three major soil categories: outwash (SCS A and B soils), till (C and some D soils), and hydric/saturated wetland soils. Postdevelopment land use can include roofs; streets, sidewalks, and parking areas; landscaped areas; pasture; and pond in addition to forest. In other parts of the country the model would include other soil and vegetation categories representative of those regions.

The user inputs the number of acres of predevelopment land use in each of the different land categories and does the same for the proposed development. For residential development, there is the option to include LID practices such as roof runoff infiltration or dispersal and porous pavement. These LID credits reduce runoff and stormwater facility size.

The user selects the type of stormwater control facility to include in the analysis. The available types are standard trapezoidal pond; tank (cylindrical, arched); vault; and irregular-shaped pond. The user can select one, two, or three orifices and a riser with a flat or notched weir (notch types include rectangular, V-shaped, and Sutro). The facility can include infiltration, if appropriate for the site. The facility can be either manually sized to meet the Department of Ecology's standards or the user can use the WWHM's pond optimization feature (AutoPond) to size the facility. An example of the WWHM pond information input form is shown in Figure 4.

AutoPond uses a complex set of rules to select pond dimensions and outlet orifice diameters and heights. Once AutoPond has made an initial selection of pond and orifice sizes, the WWHM runs HSPF to generate the 40-plus years of hourly runoff. The runoff is routed through the stormwater control facility and a flow duration comparison is made with the predevelopment flows. If the postdevelopment flow duration results do not pass the Department of Ecology flow control standard criteria, AutoPond changes dimensions and tries again. If the postdevelopment flow duration results pass the standard, AutoPond tries to make the pond smaller. This process produces the smallest (and most efficient) pond possible to meet the standard. At any time during this process the user has the option to stop AutoPond and make manual changes, if desired.

The user has the option of adding a water-quality facility either upstream or downstream of the stormwater control facility. Placing the water-quality facility upstream takes advantage of the flow moderation it provides to the control facility. This will result in a smaller stormwater control facility. Conversely, the water-quality facility will have to be made larger to handle the greater variations in flows than if it is downstream of the control facility (which then moderates the flows to the water-quality facility).

An example of a water-quality facility is a sand filter. The user must input the hydraulic conductivity of the filter material, the filter material depth, and the dimensions of the filter facility and its outlet structure. The WWHM routes the runoff through the filter and computes the percentage of runoff filtered by the facility.





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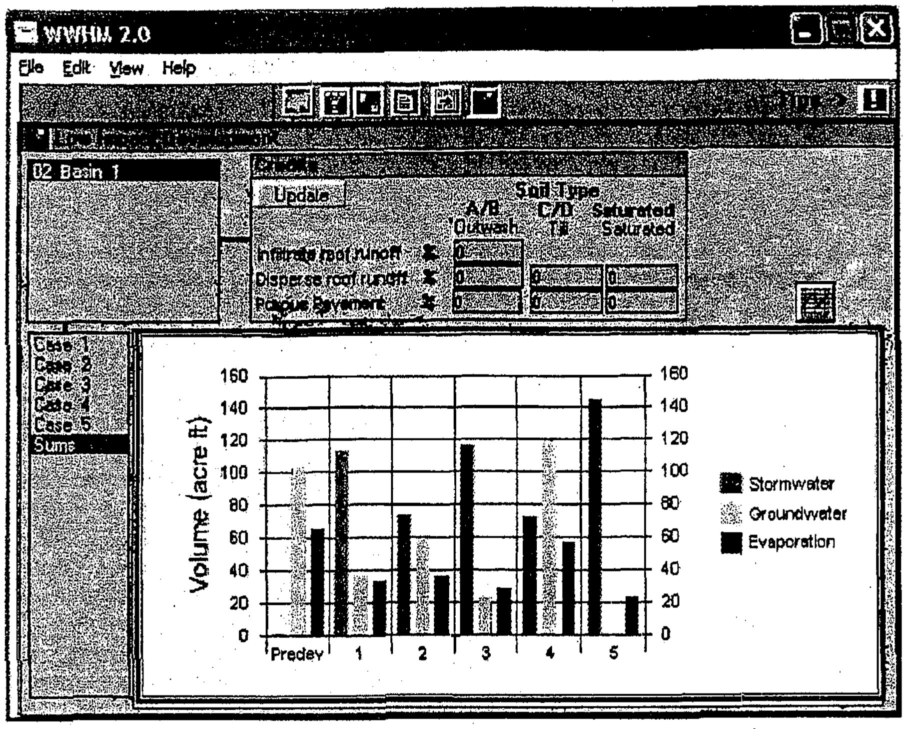
## Model Output

The WWHM produces model output in both graphical and tabular form. The major graphical output of interest is the flow duration plot of predevelopment flow and mitigated postdevelopment flow. All of the mitigated postdevelopment flow values must be on or to the left of the predevelopment values.

Numeric output is provided in tabular form. The WWHM produces a project report that lists all of the input information. This includes the precipitation station and multiplier used, both predevelopment and postdevelopment land-use types and acreages, and the dimensions and specifications of the flow control facility.

Any changes to the default parameter values or flow control standard criteria are noted in the project report. The project report also lists the number of hours the predevelopment and postdevelopment flows exceed each of the 100 flow duration levels and whether or not the flow control facility passes or fails the flow control standard for that level. Failure at any one of the 100 levels means the facility fails to meet the Department of Ecology's standard.

**Figure 5.** LID Generator (WWHM3 Prototype)




The WWHM also computes the flow rate required by the Washington Department of Ecology for water-quality treatment based on treating 91% of the total annual runoff volume. The water-quality treatment facility (which is separate from the flow control facility) can be either an online system or an offline system, depending on the user's preference.

The user has the option of saving the project file to disk. This project file can be later read into the WWHM by the user or a reviewer to check or further modify the project.

## Low-Impact Development Practices

LID practices have been recognized as opportunities to reduce or eliminate stormwater runoff at the source before it becomes a problem. LID practices typically use natural approaches to stormwater management. These include compost-amended soils, bioretention, permeable pavement, rainwater harvesting, green roofs, rain gardens, and spray irrigation. All of these approaches reduce stormwater runoff. But how much? Where does the rainfall go that does not become runoff? And how much stormwater detention storage is still required?

The answers to these questions depend on the site's climate, rainfall patterns, soils, and amount and density of development. The WWHM can be used to answer these questions because it tracks all of the precipitation's destinations (stormwater, groundwater, soil storage, and evapotranspiration). By doing so all of the impacts to the environment can be documented.

WWHM2 explicitly includes the following LID practices:

- Roof runoff dispersion on adjacent pervious land
- Roof runoff infiltration into adjacent soils
- Impervious-surface paving blocks

There are certain Department of Ecology–specified requirements for the use of any of these LID practices. For example, to use the roof runoff dispersion LID practice, the user must document that the downspouts will be directed onto splashblocks and that a vegetated flow path of at least 50 feet will be maintained between the discharge point and any property line, structure, steep slope, stream, wetland, lake, or impervious surface. No erosion or flooding of downstream properties is allowed.

WWHM2 can also be used to implicitly model compost-amended soils and green roofs. In these two cases the user must currently make changes in the WWHM HSPF parameter values to represent these LID practices. At Aqua Terra we have used WWHM2 to analyze the effectiveness of green roofs in western Washington (Beyerlein et al. 2004). We found that they typically retain 30% to 50% of the annual rainfall and reduce standard stormwater storage requirements by 20% to 30%, based on the Department of Ecology's flow duration standard.

Interestingly enough, our modeling also found that if the soil is removed from the green roof (turning it into a "blue roof"), rainfall retention increases. Six inches of rooftop storage will fully mitigate the roof's impervious-area effects on stormwater runoff, and no additional stormwater detention storage is required to meet the flow duration standard.

WWHM version 3 (WWHM3) will come with an LID generator. The model will include an extensive selection of LID practices from which to choose to minimize stormwater runoff from new development. The user will be able to select a specific LID practice and, using the LID generator, see how the stormwater runoff changes (Figure 5). By comparing the effectiveness of the different LID practices, the user can select the one that generates the least amount of stormwater runoff and design the site and stormwater flow control facility accordingly. Or the user can select the lowest-cost LID practice and, using WWHM, compute the size of the stormwater facility needed to still meet the flow duration standard. By making these comparisons, the user can determine the least-cost solution while still meeting stormwater standards. The analysis is almost instantaneous.

The specific LID practices to be included in WWHM3 and its LID generator are dependent on what the Department of Ecology and/or other agencies want to encourage developers to use and are willing to fund for addition to WWHM3. Our preliminary discussions with California Bay Area counties indicate that they will probably be interested in different LID practices from those used in the Pacific Northwest. Their version of the software will be configured to meet their specific needs.

## Other Uses

The model's flexibility allows it to be used to solve hydrologic problems far beyond its original intent. For example, by changing the flow duration criterion, the user can compute flow durations to size low-flow fish passage culverts.

For a project for the City of Everett, WA, I used the model to produce monthly stormwater and base flow volumes for nine streams draining to Port Gardner Bay, an arm of Puget Sound. Taylor Associates of Seattle used this information together with representative pollutant concen-





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trations based on land use for each flow type to compute the total pollutant loading to the bay.

Hal Mullis of Earth Tech in Bellevue, WA, is using WWHM2 to evaluate alternative facility sites with varying portions of the study basin draining to each site. He notes, "The model works well for quickly exporting the resulting flood frequency and flow duration data for plotting in Excel. In this way I am able to easily view and compare results for numerous alternatives. An added bonus is its utility in quickly building an HSPF model that can be later modified or expanded."

The Washington State Department of Transportation is funding the addition of wetland hydroperiod analysis (analysis of wetland seasonal water-surface fluctuations) to WWHM3 to determine the biological impacts of using wetlands to mitigate highway runoff. Other transportation agencies are looking at using the model to design instream structures.

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# The Importance of Imperviousness

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The emerging field of urban watershed protection has often lacked a unifying theme to guide the efforts of its many participants--planners, engineers, landscape architects, scientists, and local officials. The lack of a common theme has often made it difficult to achieve a consistent result at either the individual development site, or cumulatively, at the watershed scale.

In this paper, a unifying theme is proposed based on a physically defined unit--imperviousness. Imperviousness here is defined as the sum of roads, parking lots, sidewalks, rooftops, and other impermeable surfaces of the urban landscape. This variable can be easily measured at all scales of development, as the percentage of area that is not "green".

Imperviousness is a very useful indicator with which to measure the impacts of land development on aquatic systems. This paper reviews the scientific evidence that relates imperviousness to specific changes in the hydrology, habitat structure, water quality and biodiversity of aquatic systems. This research, conducted in many geographic areas, concentrating on many different variables, and employing widely different methods, has yielded a surprisingly similar conclusion--stream degradation occurs at relatively low levels of imperviousness (10-20%). Most importantly, imperviousness is one of the few variables that can be explicitly quantified, managed and controlled at each stage of land development.

## THE COMPONENTS OF IMPERVIOUSNESS

Imperviousness represents the imprint of land development on the landscape. It is composed of two primary components--the rooftops under which we live, work and shop, and the transport system (roads, driveways, and parking lots) that we use to get from one roof to another. As it happens, the transport component now often exceeds the rooftop component, in terms of total impervious area created. For example, transport-related imperviousness comprised 63% to 70% of total impervious cover at the site in 11 residential, multifamily and commercial areas where it had actually been measured (City of Olympia, 1994b). This phenomenon is observed most often in suburban areas, and reflects the recent ascendancy of the automobile in both our culture and landscape. The sharp increase in per capita vehicle ownership, trips taken, and miles travelled have forced local planners to increase the relative size of the transport component over the last two decades.

Traditional zoning has strongly emphasized and regulated the first component (rooftops) and largely neglected the transport component. While the rooftop component is largely fixed in density zoning, the transport component is not. As an example, nearly all zoning codes set forth the maximum density for an area, based on dwelling units (=rooftops). Thus, in a given area, no more than one single family home can be located on each acre of land, and so forth.

Thus, a wide range in impervious cover is often seen for the same zoning category. For example, impervious area associated with medium density single family homes can range from 25% to nearly 60%, depending on the layout of streets and parking. This suggests that significant opportunities exist to reduce the share of imperviousness from the transport component.

## IMPERVIOUSNESS AND RUNOFF

The relationship between imperviousness and runoff may be widely understood, but it is not always fully appreciated. Figure 1 illustrates the increase in the site runoff coefficient as a result of site imperviousness, developed from over 40 runoff monitoring sites across the nation. The runoff coefficient ranges from zero to one, and expresses the fraction of rainfall volume that is actually converted into storm runoff volume. As can be seen, the runoff coefficient closely tracks percent impervious cover, except at low levels where soils and slope factors also become important. In practical terms, this means that the total runoff volume for a one acre parking lot (Rv=0.95) is about 16 times that produced by an undeveloped meadow (Rv=0.06).

To put this in more understandable terms, consider the runoff from a one-inch rainstorm. The total runoff from a one acre meadow would fill a standard size office to a depth of about two feet (218 cubic feet). By way of comparison, if that same acre was completely paved, a one-inch rainstorm would completely fill your office, as well as the two next to it. The peak discharge, velocity and time of concentration of stormwater runoff also exhibit a striking increase after a meadow is replaced by a parking lot.

It is thought that groundwater recharge decreases as impervious cover increases, due to lower infiltration during storms. This, in turn, should translate into lower dry weather stream flows. Actual data, however, that demonstrates this effect is rare. Indeed, Evett (1994) could not find any statistical difference in low stream flow between urban and rural watersheds, after analyzing 16 North Carolina watersheds. Simmons and Reynolds (1982) did note that dry weather flows dropped 20 to 85% after development in several urban watersheds in Long Island, New York.

It should be noted that transport-related imperviousness often exerts a greater hydrological impact than the rooftop-related imperviousness. In residential areas, runoff from rooftops can be spread out over pervious areas, such as backyards, and are not always directly connected to the storm drain system. This may allow for additional infiltration of runoff. Roads and parking lots on the other hand, are usually directly connected to the storm drain system.

## IMPERVIOUSNESS AND THE SHAPE OF STREAMS

Confronted by more severe and more frequent floods, stream channels must respond. They typically do so by increasing their cross-sectional area to accommodate the higher flows. This is done either through widening of the stream banks, downcutting of the stream bed, or frequently, both. This phase of channel instability, in turn, triggers a cycle of streambank erosion and habitat degradation.

The critical question is at what level of development does this cycle begin?. Recent research models developed in the Pacific Northwest (Booth, 1991, and Booth and Reinelt, 1993) suggest that a threshold for urban stream stability exists at about 10% imperviousness. Watershed development beyond this threshold consistently resulted in unstable and eroding channels. The rate and severity of channel instability appears to a function of subbankfull floods (Hollis, 1975, Schueler, 1987, MacRae and Marsalek, 1992), whose frequency can increase by a factor of 10 even at relatively low levels of imperviousness.

A major expression of channel instability is the loss of instream habitat structures, such as the loss of pool and riffle sequences and overhead cover, a reduction in the wetted perimeter of the stream and the like. A number of methods have been developed to measure the structure and quality of instream habitat in recent years (Plafkin et al, 1989, Gibson et al, 1993, and Galli, 1993). Where these tools have been applied to urban streams, they have consistently demonstrated that a sharp threshold in habitat quality exists at approximately 10 to 15% imperviousness (Shaver et al, 1994, Booth, 1993, Galli, personnel communication). Beyond this threshold, urban stream habitat quality is consistently classified as poor.

## IMPERVIOUSNESS AND WATER QUALITY

Impervious surfaces collect and accumulate pollutants deposited from the atmosphere, leaked from vehicles or derived from other sources. During storms, accumulated pollutants are quickly washed off, and are rapidly delivered to aquatic systems.

Monitoring and modeling studies have consistently indicated that urban pollutant loads are directly related to watershed imperviousness. Indeed, imperviousness is the key predictive variable in most simulation and empirical models used to estimate pollutant loads. For example, the Simple Method assumes that annual pollutant loads are a direct function of watershed imperviousness (Schueler, 1987), as imperviousness is the key independent variable in the equation.

*Threshold Limits for Maintaining Background Pollutant Loads*
Suppose that a watershed drains to a lake that is phosphorus- limited. Further assume that the present background load of phosphorus from a rural land use amounts to 0.5 lbs/ac/yr. The Simple Method predicts that the postdevelopment phosphorus load will exceed background loads once watershed imperviousness exceeds 20 to 25% I, thereby increasing the risk of nutrient overenrichment in the lake.

Urban phosphorus loads can be reduced when urban best management practices (BMPs) are installed, such as stormwater ponds, wetlands, filters or infiltration practices. Performance monitoring data indicates that BMPs can reduce phosphorus loads by as much as 40 to 60%, depending on the practice selected. The impact of this pollutant reduction on the postdevelopment phosphorus loading rate from the site is shown in Figure 3. The net effect is to raise the phosphorus threshold to about 35% to 60% imperviousness, depending on the performance of the BMP we install. Therefore, even when effective practices are widely applied, we eventually cross a threshold of imperviousness, beyond which we cannot maintain predevelopment water quality.

## IMPERVIOUSNESS AND STREAM WARMING

Impervious surfaces both absorb and reflect heat. During the summer months, impervious areas can have local air and ground temperatures that are 10 to 12 degrees warmer than the fields and forests that they replace. The trees that could have provided shade to offset the effects of solar radiation are absent, as well.

Water temperature in headwater streams is strongly influenced by local air temperatures. Stream temperatures throughout the summer are increased in urban watersheds, and the degree of warming appears to be directly related to the imperviousness of the contributing watershed (Galli, 1991). He monitored five headwater streams in the Maryland Piedmont over a six month period that had differing levels of impervious cover. Each of the urban streams had mean temperatures that were consistently warmer than a forested reference stream, and the size of the increase (referred to as the delta-T) appeared to be a direct function of watershed imperviousness. Other factors, such as lack of riparian cover and ponds, were also demonstrated to amplify stream warming, but the primary contributing factor appeared to be watershed impervious cover (Galli, 1991).

## IMPERVIOUSNESS AND STREAM BIODIVERSITY

The health of the aquatic ecosystem is a strong environmental indicator of watershed quality. A number of research studies have recently examined the links between imperviousness and the biological diversity in streams. Some of the key findings from this body of research are summarized in Table 2.

*Aquatic Insects*
The diversity, richness and composition of the benthic or streambed community has frequently been used to evaluate the quality of urban streams. Not only are aquatic insects a useful environmental indicator, but they also form the base of the stream food chain in most regions of the country.

Klein (1979) was one of the first investigators to note that macroinvertebrate diversity drops sharply in urban streams in Maryland. He found that diversity consistently became poor when watershed imperviousness exceeded 10% to 15%. The same basic threshold has been reported by all other research studies that have looked at macroinvertebrate diversity in urban streams.

In each study, sensitive aquatic insects species were replaced by ones that were more tolerant of pollution and hydrologic stress. Species such as stoneflies, mayflies and caddisflies largely disappear and were replaced by chironomids, tubificid worms, amphipods, and snails. Species that employ specialized feeding strategies--shredding leaf litter, grazing rock surfaces, filtering organic matter that flows by, and preying on other insects-- were lost.

A typical example of the relationship between imperviousness and macroinvertebrate diversity is shown in Figure 5. The graph summarizes the trend in diversity for 23 sampling stations in headwater streams of the Anacostia watershed (Schueler and Galli, 1992). While good to fair diversity was noted in all headwater streams with less than 10% imperviousness, nearly all stations with 12% or more impervious cover recorded poor diversity. The same sharp drop in macroinvertebrate diversity at around 12 to 15% imperviousness was also observed in streams in the coastal plain and piedmont of Delaware (Shaver et al,1994).

Other studies have utilized other indicators to measure the impacts of urbanization on stream insect communities. For example, Jones and Clark (1987) monitored 22 stations in Northern Virginia and concluded that benthic insect diversity composition changed markedly after watershed population density exceeded 4 or more individuals per acre. The population density roughly translates to half-acre or one acre lot residential land use, or perhaps 10 to 20% imperviousness.

Steedman (1988) evaluated 208 Ontario stream sites, and concluded that benthic diversity shifted from fair to poor at about 35% urban land use. Since "urban land" includes both pervious and impervious areas, the actual threshold in the Ontario study may well be closer to 7 to 10% imperviousness (Booth, 1994). Steedman also reported that urban streams with intact riparian forests had higher diversity than those that did not, for the same level of urbanization.

While the exact point at which stream insect diversity shift from fair to poor is not known with absolute precision, it is clear that few, if any, urban streams can support diverse benthic communities at moderate to high levels of imperviousness (25% or more). For example, Benke (1981), Garie and McIntosh (1986), Yoder (1991) and Black and Veatch (1994) all failed to find stream insect communities with good or excellent diversity in any highly urban stream.

*Fish Surveys*
The abundance and diversity of the fish community can also serve as an excellent environmental indicator. Surprisingly, relatively few studies have examined the influence of imperviousness on fish communities in headwater streams. The results of one study is illustrated in Figure 6. Four similar subwatersheds in the Maryland Piedmont were sampled for the number of fish species present. As the level of watershed imperviousness increased, the number of fish species collected dropped. Two sensitive species were lost as imperviousness increased from 10 to 12% (trout and sculpin), and four more were lost when impervious cover increased to 25%. Significantly, only two species remained in the fish community at 55% imperviousness. Sensitive species, defined as those with a strong dependence on the substrate for feeding and/or spawning, showed a more precipitous decline. Klien (1979) found a similar relationship between fish diversity and watershed imperviousness in several dozen headwater streams in the Maryland Piedmont.

Salmonoid fish species (trout and salmon) and anadromous fish species appear to be most negatively impacted by imperviousness. Trout have stringent temperature and habitat requirements, and seldom are present in mid-Atlantic watersheds where imperviousness exceeds 15% (Galli, personal communication). Declines in trout spawning success are evident above 10% I (Galli, 1994). In the Pacific Northwest, research by Luchetti and

Feurstenburg (1993) indicate that sensitive coho salmon were seldom found in watersheds beyond 10 or 15% imperviousness. Booth (1994) noted that most urban stream reaches had poor quality fish habitat when I exceeded 8 to 12%.

Fish species that migrate from the ocean to spawn in freshwater creeks are also very susceptible to the impacts of urbanization, due to fish barriers, pollution, flow changes and other factors.. For example, Limburg and Schmidt (1990) discovered that the density of anadromous fish eggs and larvae declined sharply after a 10% imperviousness threshold was surpassed in 16 subwatersheds draining to the Hudson River.

## THE INFLUENCE OF IMPERVIOUSNESS ON OTHER URBAN WATER RESOURCES

Several other studies point to the strong influence of imperviousness on other important aquatic systems such as shellfish beds and wetlands.

Even relatively low levels of urban development yield high levels of bacteria, derived from urban runoff or failing septic systems. These consistently high bacterial often result in the closure of shellfish beds in coastal waters, and it is not surprising, that most closed shellfish beds are in close proximity to urban areas. Indeed, Duda (1982) maintains that it is difficult to prevent shellfish closure when more than one septic drain field is present per seven acres--a very low urban density. Although it is widely believed that urban runoff accounts for many shellfish bed closures (now that most point sources have been controlled), no systematic attempt has yet been made to relate watershed imperviousness to the extent of shellfish bed closures.

Taylor (1993) examined the effect of watershed development on 19 freshwater wetlands in King County, Washington, and concluded that the additional stormwater contributed to greater annual water level fluctuations (WLF). When the annual WLF exceeded about 8 inches, the richness of the both the wetland plant and amphibian community dropped sharply. This increase in WLF began to occur consistently when upstream watersheds exceeded 10 to 15% imperviousness.

## IMPLICATIONS AT THE WATERSHED LEVEL

The many independent lines of research reviewed here converge toward a common conclusion-- that it is extremely difficult to maintain predevelopment stream quality when watershed development exceeds 10 to 15% impervious cover. What implications might this apparent threshold have for watershed planning?

*Should Low Density and High Density Development be Encouraged?*
At first glance, it would seem appropriate to limit watershed development to no more than 10% total impervious cover. While this approach may be wise for an individual "sensitive" watershed, it is probably not practical as a uniform standard. Only low density development would be feasible under a ten percent zoning scenario, perhaps one acre lot residential zoning, with a few widely scattered commercial clusters. At the regional scale, development would be spread over a much wider geographic area than it would otherwise have been. At the same time, additional impervious area (in the form of roads) would be needed to link the community together.

Paradoxically, the best way to minimize the creation of additional impervious area at the regional scale is to concentrate it in high density clusters or centers. The corresponding impervious cover in these clusters is expected to be very high (25% to 100%), making it virtually impossible to maintain predevelopment stream quality. A watershed manager must then confront the fact that to save one stream's quality it may be necessary to degrade another.

A second troubling implication of the impervious/stream quality relationships involves the large expanses of urban areas that have already been densely developed. Will it be possible to fully restore stream quality in watersheds with high impervious cover? Some early watershed restoration work does suggests that biological diversity in urban streams can be partially restored, but only after extensive stormwater retrofit and habitat structures are installed. For example, fish and macroinvertebrate diversity has been partially restored in one tributary of Sligo Creek, Maryland, (Galli, pers comm). In other urban watersheds, however, comprehensive watershed restoration may not be feasible, due to a lack of space, feasible sites, or funding.

*A Proposed Scheme for Classifying Urban Stream Quality Potential*
The thresholds provide a reasonable foundation to classify the potential stream quality in a watershed, based on the ultimate amount of impervious cover. One such scheme is outlined in Table 3. It divides urban streams into three management categories based on the general relationships between impervious cover and stream quality:

1. Stressed Streams: (1 to 10% Impervious cover)
2. Impacted Streams:(11 to 25% Impervious cover)
3. Degraded Streams:(26 to 100% Impervious cover)

The resource objective and management strategies in each stream category differ to reflect the potential stream quality that can be achieved. The most protective category are "Stressed Streams" in which strict zoning, site impervious restrictions, stream buffers and best management practices are applied to maintain predevelopment stream quality. "Impacted Streams" are above the threshold, and can be expected to experience some degradation after development (i.e., less stable channels and some loss of diversity). The key resource objective for these streams is to mitigate these impacts to the greatest extent possible, using effective best management practices.

The last category of "Degraded Streams" recognizes that predevelopment channel stability and biodiversity cannot be fully maintained, even when best management practices or retrofits are fully applied. The primary resource objective in degraded streams shifts to protect downstream water quality by removing urban pollutants. Efforts to protect or restore biologically diversity in degraded streams are not abandoned; in some priority subwatersheds intensive stream restoration techniques are employed to attempt to partially restore some aspects of stream quality. In other subwatersheds, however, new development (and impervious cover) is encouraged to take place (so as to protect stressed and impacted streams).

*Watershed-based Zoning*
Watershed-based zoning is based on the premise that impervious cover is a superior measure to gauge the impacts of growth, compared to population density, dwelling units or other factors. The key steps in watershed-based zoning are as follows. *First*, a community undertakes a comprehensive physical, chemical and biological monitoring program to asses the current quality of its entire inventory of streams. The data is used to identify the most sensitive stream systems, and to refine impervious/stream quality relationships. *Next*, existing imperviousness is measured and mapped at the subwatershed level. Projections of future impervious cover due to forecasted growth are also made at this time.

The *third* step involves designating the future stream quality for each subwatershed based on some adaptation of the urban stream classification scheme presented earlier. The existing land use master plan for is then modified to ensure that future growth (and impervious cover) is consistent with the designated stream classification for each subwatershed.

The *final* step in the watershed-based zoning process involves the adoption of specific resource objectives for each stream and subwatershed. Specific polices and practices on impervious cover limits, best management practices, and buffers are then instituted to meet the stream resource objective, that are to be directly applied to future development projects.

Watershed-based zoning should provide managers with greater confidence that resource protection objectives can be met in the face of future development. It also forces local governments to make hard choices about which streams will be fully protected, and those that will become at least partially degraded. Some environmentalists and regulators will be justifiably concerned about the streams whose quality is explicitly sacrificed under this scheme. The explicit stream quality decisions which are at the heart of watershed-based zoning, however, are preferable to the uninformed and random "non-decisions" that are made every day under the present zoning system.

*A Cautionary Note*
While the research on the links between impervious cover and stream quality are compelling, it is doubtful whether it can serve as the sole foundation for legally defensible zoning and regulatory actions at the current time. One key reason is that the research has not been standardized. Different investigators, for example, have used different methods to define and measure imperviousness. Second, researchers have employed a wide number of techniques to measure stream quality characteristics that are not always comparable to each other. Third, most of the studies have been confined to few ecoregions in the country. Little research has been conducted in the Northeast, Southeast, and Midwest and semi-arid regions of the West. Lastly, none of the studies has yet examined the effect of widespread application of best management practices on impervious cover/stream quality relationships. Until a controlled study is undertaken to determine how much BMPs can "cheat" the impervious cover/stream quality relationship, it can be argued that structural practices alone can compensate for the effects of imperviousness.

On the positive side, it may be possible for a community to define the impervious cover/stream quality relationship in a short time frame at relatively low cost. A suggested protocol for conducting a watershed monitoring study is presented in Table 4. The protocol emphasizes comparative sampling of a large population of urban subwatersheds of different increments of imperviousness (perhaps 20 to 50).

A rapid sampling program collects consistent data on hydrologic, morphologic, water quality, habitat and biodiversity variables within each subwatershed. For comparison purposes, series of undeveloped and undisturbed reference streams is also monitored. The sampling data is then statistically and graphically analyzed to determine the presence of imperviousness/stream quality relationships.

The protocol can be readily adapted to examine the impacts of best management practices in shifting the stream quality/impervious relationship. This is done by adjusting the sampling protocol to select two groups of study subwatersheds--those that are effectively served by best management practices and those that are not.

*Minimizing Impervious Cover at the Site*

Reducing impervious cover can be an effective element of the overall BMP system for a development site. As noted earlier, imperviousness need not be a fixed quantity. A site designer can utilize a wide range of techniques to minimize impervious cover at development site that collectively can reduce imperviousness by 10 to 50% (See Technical Notes 38 and 39 in this issue).

**CONCLUSION**

Research has revealed that imperviousness is a powerful and important indicator of future stream quality, and that significant degradation occurs ar relatively low levels of development. The strong relationship between imperviousness and stream quality presents a serious challenge for urban watershed managers. It underscores the difficulty in maintaining urban stream quality in the face of development.

At the same time, imperviousness represents a common currency that can be measured and managed by planners, engineers and landscape architects alike. It links the activities the individual development site with its cumulative impact at the watershed scale. With further research, impervious cover can serve as an important foundation for more effective land use planning decisions.

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# CHANNEL PROTECTION

**Ted Brown and Deb Caraco**

## INTRODUCTION

It is widely accepted that urbanization can alter the geometry and stability of stream channels. Both anecdotal evidence and field research support the notion that the larger and more frequent discharges that accompany watershed development cause downstream channels to enlarge, whether by widening, downcutting, or a combination of both (Figure 1). Channel enlargement severely degrades the quality of instream habitat structure and sharply increases the annual sediment yield from the watershed. These two factors, in turn, are often correlated with the sharp drop in aquatic diversity frequently observed in urban streams (U.S. EPA, 1997).

Despite the large body of research available, many questions about the channel enlargement process in urban and suburban streams remain to be answered. For example, how much development can occur before a stream response is observed? Exactly how much will a channel enlarge, and how many years will it take to do so? Finally, what stormwater management strategies can engineers use to mitigate the amount of future channel enlargement?

While it is not easy to predict the absolute degree of channel enlargement caused by watershed development, it is clear that enlargement will occur in the absence of stormwater controls (Figure 2). Therefore, the challenge facing the engineering community is to develop and adopt stormwater management criteria that will provide adequate channel protection to minimize the extent of future channel enlargement.

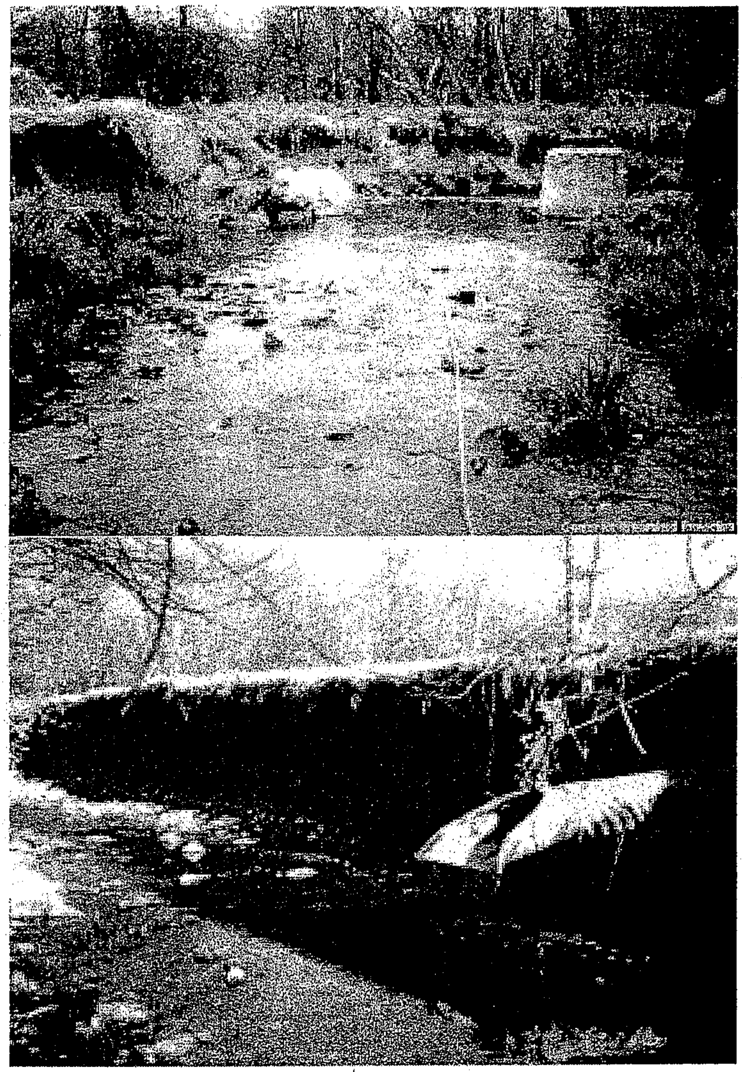

Figure 1. Examples of Channel Enlargement as a Consequence of Urbanization.

## OPTIONS FOR CHANNEL PROTECTION CRITERIA

Historically, efforts to control channel erosion through stormwater management have been largely unsuccessful. The failure has, in part, been the result of an oversimplification of geomorphological processes. In the past, engineers reasoned that if natural channels are largely formed by "bankfull" storm events that occur on average once every one or two years (Leopold *et al.*, 1964), then stormwater ponds should detain the post-development peak discharge for the two-year storm to the predevelopment level (i.e., two-year storm control). There are two problems with this approach. First, while the magnitude of the peak discharge may not change from pre- to post-development with two-year control, the duration of erosive flows increases (Figure 3). This may actually exacerbate channel erosion since banks are exposed to a longer duration of erosive bankfull and subbankfull events (MacRae, 1993, 1996; McCuen and Moglen, 1988). Second, with increased development and associated increased runoff, the bankfull event often shifts to rainfall events smaller than the two-year return frequency. Consequently, the total

*Channel enlargement in urbanizing streams can have significant economic and ecologic implications, from impacts to infrastructure*

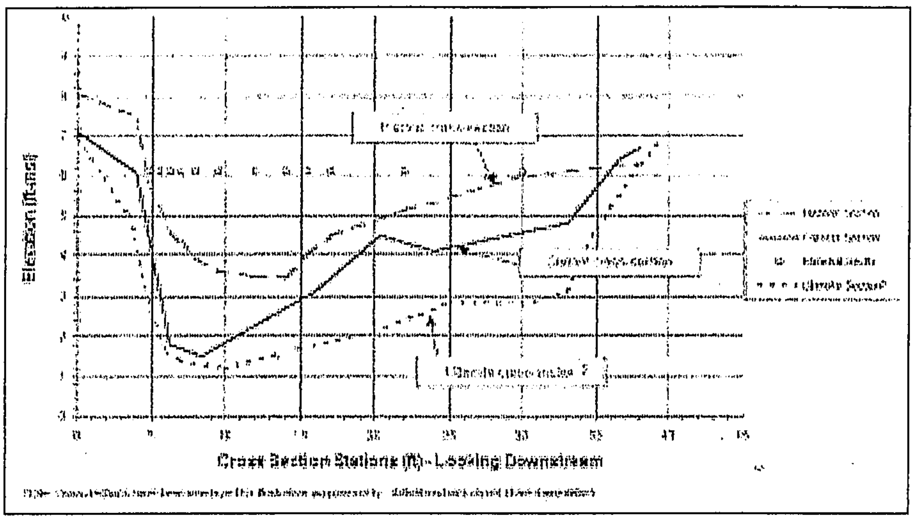


Figure 2. Illustration of Channel Cross Section Over Time (Brown and Claytor, 2001).

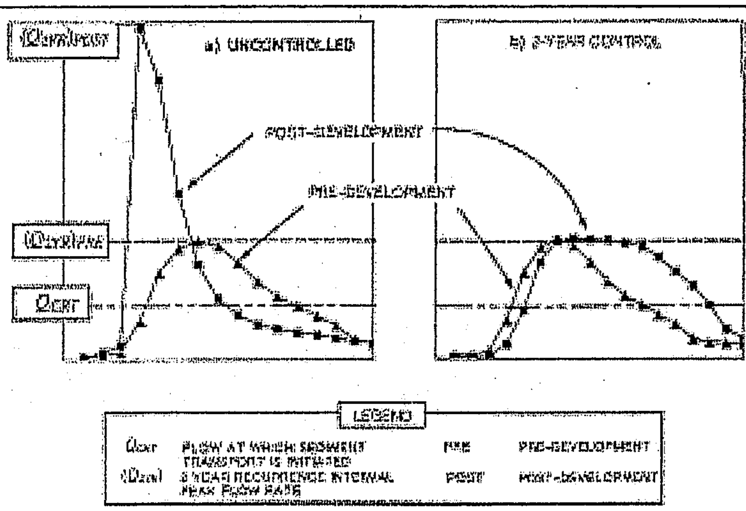


Figure 3. No. Control vs. Two-Year Control (MacRae and Rowney, 1992).

energy available to transport bed materials can actually increase when two-year peak discharge control is used.

The choice of two-year storm control neglects the increased frequency of bankfull and sub-bankfull flows in urban watersheds. For example, Leopold (1994) observed that the average number of bankfull flow events in an urbanizing watershed near Washington, D.C., increased from two to seven times per year between 1958 and 1987.

Over time, practitioners have developed a better understanding of the key parameters to provide adequate downstream channel protection. With the advent of more sophisticated computer software, much of the analysis of channel geomorphology and protection criteria has been based on hydrologic and hydraulic modeling of streams. In addition, the limited field data that have been collected for some of the methodologies are favorable and support the use of these methodologies to protect channels from accelerated channel erosion. Generally speaking, the newer methodologies require more control (i.e., a larger required storage volume) than traditionally has been allocated to channel protection. One of the challenges of the more advanced channel protection approaches is to develop design methodologies that are relatively easy to apply. Three of the more promising approaches are described below briefly.

Two-Year Over-Control

This method (initially proposed by McCuen, 1979) is based on controlling the post-development peak flow rate to 50 percent or less of the predevelopment level. Another common numerical approach is to control the two-year post-development discharge rate to the one-year predevelopment rate, using the 24-hour storm event. Subsequent analysis by MacRae (1993), however, indicates that this design criterion is still not fully capable of protecting the stream channel from erosion. Modeling suggests that, depending on the bed and bank material, the channel may either degrade (downcut where soft boundary material is present) or aggrade (build up where firm boundary material is present) with over control.

Distributed Runoff Control (DRC)

This method was developed by MacRae (1993) and is proposed for adoption in Ontario, Canada (Aquafor Beech, 1999) and on a limited basis in the State of Vermont (VTANR, 2001). The DRC method involves detailed field assessments and hydraulic and hydrologic modeling to determine the hydraulic stress and erosion potential of bank materials. The methodology is based on the premise that channel erosion is minimized if the erosion potential of the channel bank materials remains the same as in predevelopment conditions over the range of flows at which sediment transport of bed or bank material begins (i.e., mid-bankfull to bankfull flow events). While the method holds great promise and has been applied and tested recently in Ontario, it requires some detailed field work at each site. The DRC hydrograph attempts to mimic the predevelopment hydrograph for the area above $Q_{crt}$ (flow at which sediment transport is initiated) shown in Figure 4.

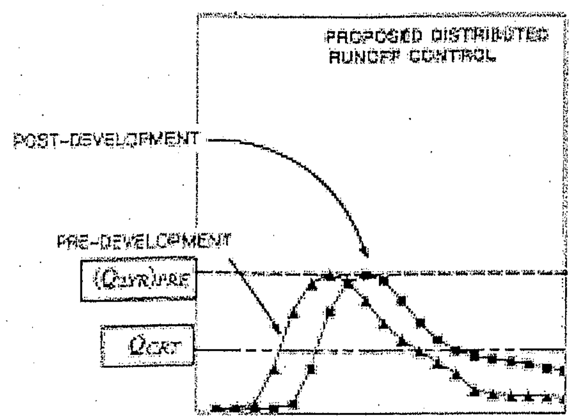


Figure 4. Distributed Runoff Control (DRC) vs. Predevelopment Hydrograph (MacRae and Rowney, 1992).

24-Hour Extended Detention of the One-Year Storm

This design method calls for holding the runoff volume generated by the one-year, 24-hour rainfall to be gradually released over a 24-hour period (MDE, 2000). The rainfall depth will vary depending on location and can be determined from intensity-duration-frequency [IDF] curves or other regional rainfall frequency analyses (e.g., NOAA Atlas 2 or TP 40). The premise of this approach is that runoff will be stored and released so gradually that critical erosive velocities will seldom be exceeded in downstream channels. Modeling based on a Maryland development site demonstrated that 24-hour extended detention approximated DRC well for storms less than the two-inch rainfall (Capuccitti and Page, 2000). The required storage volume needed for 24-hour detention of the one-year storm is not trivial; it is roughly comparable to the storage volume for ten-year peak discharge control.

It is of note that the 24-hour extended detention of the one-year storm event has been adopted in Maryland as the base channel protection criteria and is proposed for adoption in the states of New York, Vermont, and Georgia. The advantages of this approach over the DRC are that it is relatively easy to apply (in terms of computing the runoff volume and storage requirements), it is conducive to regional or statewide application, and it does not require extensive field measurements.

LIMITATIONS TO CHANNEL PROTECTION REQUIREMENT

From a programmatic and design standpoint, there are practical limitations on how broadly a channel protection criterion can be applied. Namely, there is a minimum site size at which the required orifice or weir sizes become too small to effectively operate and maintain. In addition, channel protection is generally not needed where sites discharge directly to a river (e.g., fourth order or greater), lake, reservoir, or estuary.

In addition, in streams where channel erosion is already occurring, it may be necessary to supplement the upstream channel protection storage with some form of in-stream channel protection controls. Representative practices range from robust bank protection measures such as imbricated riprap, boulder revetments, and root wads to grade control practices such as vortex weirs, cross veins, and step pools to "softer" bioengineering practices such as live fascines and coir fiber logs. A study by Brown (2000) indicates that most stream restoration practices work reasonably well in urban stream systems when sized, located, and installed correctly. The efficacy and longevity of these in-stream controls tends to improve when they are used in combination with upstream storage controls.

CONCLUSION

Channel enlargement in urbanizing streams can have significant economic and ecologic implications, from impacts to infrastructure such as culverts, sewers, bridges or pipelines to impacts on water quality and biology such as increased sediment loads, habitat loss and fish barrier creation. Consequently, there is a heightened need for stormwater engineers and managers to develop and assess stormwater design criteria that directly address the channel enlargement problem. While there are some promising approaches that are being applied in different regions of the country, more research is needed to determine how well these new criteria prevent or minimize the channel enlargement process.

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## ▲ Employment Opportunity

**Comments on by Thomas Dunne, University of California Santa Barbara on**

***Hydromodification Management Plan Report (incl. Appendices)***
**by the Santa Clara Valley Urban Runoff Pollution Prevention Program, Public Review Draft June 2004**

**and**

***Technical Requirements and Geographic Areas for Hydromodification Management in Santa Clara Valley Basin***
**by GeoSyntec Consultants and others, Final Report June 2004**

The consultants have developed and implemented an attractive procedure for designing how to control the processes most likely to accelerate stream channel erosion as a result of urban development in a watershed. The method is broad and systematic, involving a set of recently developed tools and insights developed mainly in the 1990s about how to improve predictions of the effects of land surface alteration on hydrologic response and its effects on channel networks.

The power of the method arises from its combination of systematic field surveys, computer-assisted modeling, and capacity for efficiently examining alternative control strategies. The model-based approach provides transparency (assuming adequately thorough review) and reproducibility by various analysts. The field surveys allow for local calibration of the threshold conditions that destabilize channels, for checks of the realism of the model predictions, and for overcoming some of the limitations of the modeling approach through monitoring. The use of computerized tools for data storage and modeling allows cumulative watershed effects to be analyzed for an entire channel network, long weather records to be utilized in the computations, and for alternative control strategies to be reviewed efficiently.

The conceptual model underpinning the method incorporates modern ideas about the value of simulating continuous flow records to reflect watershed and channel geometry, watershed surface, and the recorded probability distribution of rainstorms. It also incorporates the idea, widely observed in all but large, perennial, vegetation-free sandy channels, that some critical threshold discharge is required to initiate channel erosion, either by mobilizing the bed or attaining a high enough stage to scour the weaker sediments of the channel bank. The method also recognizes from the literature of the 1990s that since urbanization causes significant flow increases even in frequent, moderate storms that the frequency and duration of the enhanced flows must be taken into account. Thus, instead of simply computing the effects of urban development on selected "representative" or "dominant" instantaneous peak flows as in past practice, the consultants have focused on the large increases in the duration of small to moderate floods that are enhanced by urbanization. They examine the magnitude and duration of the resulting shear stress compared to a critical value assigned to represent the resistance of the bank material, and convert this excess shear stress to a value of work through multiplying by an index of flow velocity and integrating the results over the duration of the flows simulated from a long rainfall record. Having acknowledged that this approach of concentrating on the moderate, frequent storms is likely to account for most of the problem, I note that the research that has produced this result is based largely on modeling and does not yet have a strong empirical base (such as erosion surveys along channels after large storms), and thus there is one reason (among others to be described later) for continuing to monitor the watersheds of interest to keep track of unforeseen changes.

The calculations of average annual work at flows (shear stresses) above the critical value needed for bed or bank erosion are used to develop an erosion potential index, which is a ratio of post-development energy expenditure to pre-development energy expenditure at the same place. This erosion potential (determined by both upstream watershed conditions and climate and the extent and nature of watershed development) is related to the risk of channel erosion through logistic regression that incorporates the systematic field surveys. This step is innovative and crucial for assessing risk of channel destabilization. For this reason, I suggest that a follow-up analysis be made of the sensitivity of the results to various uncertainties that are implicit in the method. My suggestion is made because of the attractiveness of the method for assigning risk of watershed-scale effects.

The sensitivity analysis might include the following topics. At present the definition of "medium/high erosion" conditions or "unstable conditions" that are used for calculating risk by the logistic regression (Figures 3-5 and 3-6 in HMP) are not defined explicitly enough for external evaluation. It would be useful to find out how much operator variance exists in the field identification of the channel stability condition, and how this variance affects the prediction of risk. It would also be valuable to know how susceptible the method is to uncertainties in the flow modeling. There is a brief reference in the report to validation of the simulations against observed high flows and the results were encouraging. However, it should be recognized that the test was not a very demanding one. The three streams used for the modeling are all gauged, so that local data could be used for model calibration and then the validation occurred on the same stream that was used for the calibration. A more common and demanding test of model accuracy arises when the flow model is applied to predict flows in an ungauged basin (most basins), where significant errors usually arise in the prediction of individual hydrographs. I cannot anticipate whether this will cause large uncertainties in the erosion potential (which is averaged over many individual predicted hydrographs), but it would be interesting for future applications of the method to know how much uncertainty arises in predicting the risk of channel instability because of hydrologic prediction and field definition of channel instability.

In the case of the Santa Clara River basin, of course, there is a useful amount of local gauging data, and the method is being investigated as it applies to three representative subwatersheds before extrapolation to the entire basin, so there are favorable conditions for a limited degree of extension of the predictions outside of an observed range. However, there remains some uncertainty in the prediction, especially as it applies to future buildout conditions (as recognized by using the concept of risk), and this is where the systematic field observations will become valuable (see later).

There is some ambiguity in the original presentation of the method (HMP Figure 3-2 and equation 1) about whether or when the channel resilience is to be represented by the permissible flow velocity for the bank material or the critical shear stress (particle size) of the bed material. It is conceivable that this issue could be resolved on a segment-by-segment basis by qualified observers, who might recognize which of the indices is relevant to the particular site or to a particular flow range. However, it seems unlikely that such investment of labor will be possible for most applications. In the present case, on p. 51 of the *Technical Requirements Report*, this uncertainty seems to be resolved in favor of utilizing the bank material measure.

This emphasis on bank erodibility (or even bed erodibility) reflects the relevance of the assessment methodology for channels and reaches in which the primary effect of urbanization is to increase channel size, degrade beds and undermine banks, as appears to be the case in the target basins (from the field assessments). The consultants have quite reasonably avoided trying to develop a more complete methodology based on sediment transport routing, because the state of that art is not adequate to the task of developing a robust design methodology for runoff and sediment control in whole watersheds and channel systems. However, this results in a slight overstatement of the conceptual basis for the assessment methodology when the report states (HMP p. 3-2) "The stability assessment looks at the balance among flow energy, *sediment supply,* and channel resilience that exists in a stable stream." The reason for highlighting this subtle point is that, because it cannot explicitly represent sediment supply and sediment transport capacity, the method is likely to 'overlook' a condition where sediment eroded from an upstream reach because of flow enhancement leads to aggradation where the channel gradient decreases suddenly downstream. In such a reach, the channel bed is often inundated with finer sediment or even becomes filled completely with sediment and the flows spread across the valley floor, sometimes causing bank undermining or tree mortality where, in the absence of the upstream sediment supply, the channel gradient would have maintained a low erosion potential even under the enhanced flow regime. Fortunately, the availability of computer tools already used in the method could be used to search systematically for reaches where this aggradation might be a problem. The software used for setting up the HEC-HMS modeling could be used to search channel networks for reaches with strong decreases in gradient downstream of reaches with a high risk of channel instability. These sites could be flagged for more detailed analysis and monitoring.

I also suggest that some further thought be given to expressing more explicitly the likely consequences of buildout in the watershed. This is not so much a technical aspect of the methodology itself, but of how its results are to be used and communicated. For example, HMP (p. 3-18) suggests a target value for managing flows to keep the erosion potential below 1.2. It is stated that under such a circumstance, "the chances of a stream becoming unstable are 14 in 100 or less." It would be illuminating to follow this brief remark with a fuller description of the likely outcomes. Presumably, the result is implying that 14 percent of all the reaches for which the erosion potential rises to about 1.2 could become unstable. How many miles of channel are likely to be involved? Where are these unstable reaches most likely to be? How many are close to sharp reductions of channel gradient, where aggradation might set off a cascade of other consequences? Elaboration of these points could improve the use of the results by decision-making bodies.

Finally, not only have the consultants developed a useful prediction tool for planning and design of control measures, but they have also established a valuable database of systematic channel surveys throughout the sampled subwatersheds. These data, especially the reach-by-reach definition of the degree of channel 'stability' (subject to the earlier suggestion about clarifying this definition), could be used as a way of monitoring both the condition of the channel network during watershed development and, later, as a means of evaluating the prediction methodology itself. A small outlay of funds for a rapid survey every few years and after major floods could yield a lot of useful data for watershed management and even timely channel restoration if damage should occur. For this reason, attention should be paid to storing the field survey data in some easily accessible form.

Thomas Dunne

Hydrologist

**Comments by Brian Bledsoe, Department of Civil Engineering, Colorado State University on**

*Hydromodification Management Plan Report (incl. Appendices)* by the Santa Clara Valley Urban Runoff Pollution Prevention Program, Public Review Draft June 2004

and

*Technical Requirements and Geographic Areas for Hydromodification Management in Santa Clara Valley Basin* by GeoSyntec Consultants and others, Final Report June 2004

***General Comments***

I commend the project participants for developing a fundamentally solid strategy for managing hydromodification in the Santa Clara Valley. The procedure has a strong physical basis and encompasses the most critical physical processes without becoming unnecessarily complex and cumbersome. The conceptual approach also reflects the best available science. Numerous studies examining the effects of urbanization on channel stability underscore the importance of controlling the small to moderate sized events (less than a 2-year return period) that tend to be most magnified by development. The procedure necessarily relies on continuous flow simulations to quantify the duration of erosive flows and cumulative geomorphic work exceeding the threshold for erosion of limiting boundary materials. Although some practicing engineers are reluctant to move beyond single-event / design storm approaches, continuous hydrologic simulation at the time scale of decades is essential for adequately managing hydromodification in urbanizing watersheds. Combining a cumulative measure of geomorphic work and logistic analysis to link erosion potential with measured channel responses is innovative and entirely appropriate for quantifying the risk of channel instability.

Although the procedure is underpinned by sound hydrologic and geomorphic understanding, there are still are number of details that will have to be worked out to ensure physically reasonable and consistent parameterization of the models used to characterize flow changes. Model parameterization still leaves substantial latitude in characterizing pre- and post-development conditions. For example, if I hypothetically set out to minimize the flow controls required on a new project, what would prevent me from:

- Choosing unrealistically low infiltration rates for the pre-project condition?
- Choosing high infiltration rates for the post project condition despite the reality that heavy equipment compacted much of the site?
- Selecting unrepresentative stream sampling locations with relatively coarse materials and resistant boundaries?
- Picking the highest available estimate for critical shear stress for the limiting boundary material when better estimates are available in the literature?
- Placing stone grade control structures in the channel without careful analysis and claiming that I had mitigated the potential impacts to the extent practicable?

Conversely, input parameter uncertainty could also result in excessive "over control" and unwarranted costs to permit applicants. Therefore, it is critical that clear guidance be provided for parameterization in conducting HMP modeling studies. HEC-HMS, SWMM, and HSPF vary substantially in infiltration / soil storage algorithms and adequacy for modeling site-specific differences in development style and drainage infrastructure. How will consistency between new HMPs and the modeling techniques and inputs used to calibrate the risk criterion of Ep <1.2 be ensured? I currently don't see specific guidance that would prevent 'apples and oranges' comparisons. The SCS soil permeability values are notoriously inaccurate for developed lands. Results will also vary depending on how watersheds are discretized and the spatial resolution of distributed models. I strongly support the development of a standard regional model (akin to the King County, WA approach) to provide a consistent and transparent tool that constrains inputs to realistic values, and reflects the best available scientific information and latest calibration data. Moreover, geomorphic sampling must occur at a spatial density that results in representative inputs that reflect less resilient stream segments.

It is reasonable to provide options that include instream practices. But instream practices like grade control should be carefully designed in accordance with analytical stable channel design procedures and sediment transport modeling. For example, inappropriate design of grade control can store sediment and initiate headcutting in downstream reaches. If adequate standards for assessing the likely geomorphic impacts of proposed instream practices are not developed, these approaches could result in channel destabilization and degradation of designated uses.

It is important to acknowledge that the performance criteria may require adjustment and updating as more data and experiences are garnered. An important physical process that is not well represented in the approach is the potential for changes in sediment *supply*. Trapping of sediment by BMPs and the nature of development and its location relative to source areas could have important implications for channel stability and the degree of flow control required. Simply considering Lane's balance or Schumm's qualitative response tells us that perfectly matching the pre-development flow regime does not necessarily ensure channel stability, especially in "live bed," capacity-limited channels. Perhaps one of the most compelling arguments for selecting a very low risk of instability is the fact that the calibration procedure used to develop the logistic curve may not adequately account for sediment "starvation" due to BMP trapping and imperviousness. How much monitoring of channel stability will occur after an HMP is implemented? Additional channel habitat and stability data are critical for assessing the adequacy of protection provided by the management criteria and for improving the robustness of the logistic model through cross-validation.

There is a general inconsistency in the language used to describe the flow attributes of concern. "Peak flows", "duration", "rates", and "timing" are all interspersed in the document without clearly defining what is meant. Perhaps the aim could be described as controlling the overall "erosion potential" or "flow effectiveness" and the terminology could be clarified early in the document by describing how the controls relate to the various aspects of flow regime. I suggest using consistent wording throughout after defining specifically what is meant by erosion potential or some other term that encompasses the effects of altered flow peaks, durations, and rates.

The statistical analyses are appropriate. Although the risk model is based on a valuable set of geomorphic data, I recommend additional field verification and cross-validation of the logistic model over time. Of course, choosing a risk level involves politics and values. I suggest trying to help stakeholders understand that a 14% risk means that on average about one in seven stream segments will become 'unstable' and degraded, even if the controls are implemented per recommendations. Besides the costs of implementing the controls, such value judgments should also be based on consideration of larger-scale impacts potentially arising from increased downstream sediment delivery and migration of headcuts into upstream segments that were adequately protected, potential TMDL requirements, and loss of property due to bank failure. In other words, accepting some degree of instability could have geomorphic implications that extend well beyond a destabilization of a single reach of stream. This underscores the need for ongoing monitoring and analysis.

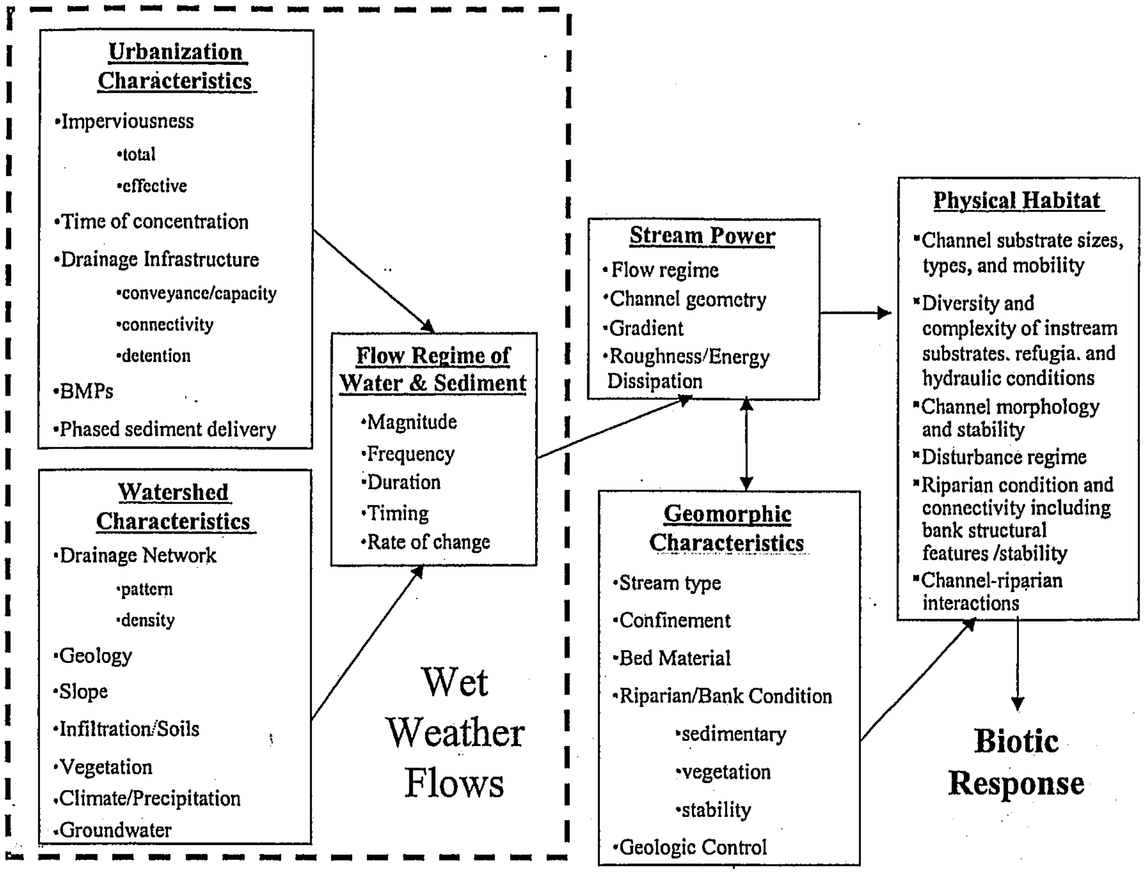
Achieving and Ep of 1.2 on a site-by-site basis is not equivalent to achieving a cumulative Ep of 1.2 in the overall system. It is analogous to the old Q2 'peak shaving' approach. Q2 peaks may be maintained site by site but synchronization of peaks can actually exacerbate flooding. The same principle applies here, despite the fact that durations are controlled. This suggests that watershed level planning could improve the likelihood of mitigating stream impacts.

It is tempting to say that the Ep analysis method is 'easy' because it only requires a representative grain size, cross-section, slope, and Manning's n value. But selecting representative values of these parameters in heterogeneous stream segments and drainage networks is not a trivial issue. Again, what sort of minimal spatial resolution is necessary? Should the modeling be targeted at relatively vulnerable reaches that could trigger larger scale responses?

I'm very glad to see the emphasis on operation and maintenance of HMP practices.

***Specific Comments***

After perusing Figure 2-1 again, it seems unnecessarily complicated, despite the complexity of the processes involved. It also seems to be missing important linkages between *sediment supply* and the surface runoff / soil type, land use w/BMP, vegetation type boxes. An oversimplification that Larry Roesner and I came up with and published in a WERF document is provided below (although this figure should more explicitly link geomorphic characteristics with sediment regime as well).




P. 3-8 The work index includes velocity to "accurately represent W in units of work." This is more of an academic comment but the statement is not entirely accurate because velocity and shear are not raised to the same exponent. It is not clear how the conversion factor works. If the exponent stays at 1.5, one could take velocity to the same power and then convert to unit bedload transport rate ala Bagnold who used specific stream power to the 1.5 power for his relationship. Yvonne Martin and Mike Church presented an

improved Bagnold equation of this form in a recent Earth Surface Processes and Landforms paper.

Pg. 3-10 How many flow bins are required? Can they be arithmetic or logarithmic? I suggest looking at Phil Soar and Colin Thorne's work for guidance on this issue.

Figure 3-6 Why are RC-1 and RC-2 located in the middle of the chart? What does the labeled arrow mean?

Pg. 3-17 Doesn't Qc potentially depend on bank erosion in addition to "bed movement?"

Pg. 3-18 The statement that the "watersheds are not significantly different to warrant…." seems to contradict statements at the top of next page and also has statistical connotations.

Pg. 3-19 The statement that "Ross Creek may be more resilient than Thompson Creek" seems tangential without further explanation. I agree that it is important to emphasize that the Ep approach is referenced to watershed-specific baseline conditions.

Pg. 4-4 The minimum duration controlled flow is set to 10% of the pre-project 2-year peak flow. Is the 2-year pre-project peak flow associated with peak flows occurring in a certain time increment (hourly, 15 min?) in the total flow series, partial duration series, or annual maximum series? If the answer is partial duration, how are the threshold and inter-event time defined?

Pg. 4-5 The circle points of varying shade on Figs. 4-1 and 4-2 are not adequately explained. Are 5-year peak flows labeled as 2-year peak flows in Fig. 4-2?

Pg. 4-12 What determines whether some combination of volume controls and instream controls meet objectives "to the maximum extent practicable"? It is good to give people options and room for creativity but this loophole seems to have the potential to undermine the objectives of the strategy. Could this be changed to say that the combination of practices must be demonstrated to provide protection equivalent to the duration/work controls or a variance be obtained? This is obviously a policy issue but it is also a scientific one in that it will be difficult, at best, to quantify what is "practicable" or equivalent.

Pg. 4-14 I hope tidally influenced areas are not exempt from water quality BMPs. Erosion of manmade conveyances can degrade designated uses of receiving tidal waters.

Pg. 4-23. The top diamond in the diagram refers to size criteria. Were these criteria described in the document? Do the size criteria refer to development size and/or stream size? How large does a channel have to be to require a HMP?

Pg. 5-7. Top of page- "mosquito production is reduces."

Pg. 5-15 SCS soil permeability values are notoriously inaccurate, especially in areas subject to compaction.

Pg. 6-8 What is a "reasonable time frame" for construction of instream controls?

References – the Western Washington document is not consistently cited in the text and is sometimes cited to as "King County."

Appendix B Pg. 34. The equation from Andrews (1983) is for armored gravel bed rivers and the D50 in the denominator is the D50 of the *subsurface* grain sizes below the coarse surface layer. Andrews and Nankervis (1995) presented new relationships of this type that are referenced to the *surface* D50. Beta in the surface referenced equations is typically between –0.9 and –1. I recommend using the best available science from mixed sand / gravel bed systems (e.g. studies by Peter Wilcock and Roger Kuhnle) to estimate critical shear stresses for bed material.

App. B, Pg. 56, Citation 5 change "Brain" to Brian

Appendix F. The discussion of logistic regression fails to mention one of the most useful and intuitive measures of logistic regression model performance: % correctly classified.

Pg. F-3. What precipitation record length is required? What flow record length is required? If a ~50 flow record is needed, will this be part of the HMP requirement? Will it be necessary to extend short precipitation records using correlations with other gages or stochastic modeling or simply repeat short records?

USING CONCEPTS OF WORK

TO EVALUATE HYDROMODIFICATION IMPACTS ON STREAM CHANNEL INTEGRITY AND EFFECTIVENESS OF MANAGEMENT STRATEGIES

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## ABSTRACT

Urbanization modifies the natural watershed and stream hydrologic and geomorphic processes by altering the landscape and introducing impervious surfaces and drainage infrastructure. Increases in volume, frequency, and duration of runoff from urban development are defined as hydromodification. Hydromodification intensifies sediment transport and leads to stream bank erosion and channel incision. The Santa Clara Valley Urban Runoff Pollution Prevention Program (Program) is required to develop a Hydromodification Management Plan (HMP). As part of developing the HMP, the Program in cooperation with the Santa Clara Valley Water District, developed and tested a method for predicting channel instability, and is in the process of establishing in-stream stability criteria, runoff control design criteria, and management measures, which include a combination of on-site, in-stream, and regional control strategies. The method predicts erosion potential (Ep) using an index representing the effective work done by flow energy in excess of the amount required to transport the available sediment load. The predicted Ep was compared to observed conditions in a test watershed and found to accurately predict stable and unstable channel conditions. A "threshold of adjustment" is identified that distinguishes between stable and unstable conditions. The Ep and threshold of adjustment are intended to be used to set management criteria and evaluate effectiveness of proposed solutions. The Ep concept also has been used to evaluate the effectiveness of control strategies.

## INTRODUCTION

It is well documented that urbanization modifies the natural watershed and stream hydrologic and geomorphic processes by introducing impervious surfaces and drainage infrastructure into a watershed (GeoSyntec, 2002; Bledsoe & Watson, 2001; Booth, 1990; Hollis, 1975; Hammer, 1972). Hydromodification is defined as increases in surface runoff volume, frequency and duration resulting from development (GeoSyntec 2002). Hydromodification intensifies sediment transport and often leads to stream channel enlargement and loss of habitat and associated riparian species (GeoSyntec, 2002; Bledsoe & Watson, 2001; Booth, 1990; MacRae, 1992).

The California Regional Water Quality Control Board (RWQCB) San Francisco Bay Region, under the National Pollutant Discharge Elimination System permit program for stormwater, is requiring dischargers to address the impacts from hydromodification. The Santa Clara Valley Urban Runoff Pollution Prevention Program (SCVURPPP) is one of the first stormwater programs subject to the new permit requirements, which includes the development of a Hydromodification Management Plan (HMP). This paper summarizes the technical study supporting the development of the HMP.

There have been many facets of this study that could be the focus of a paper. The goal of this paper is to summarize the approach (which has been published in recent conference proceedings), but focus on the *work* concepts used to predict hydromodification impacts and describe how these concepts are used to make management decisions and develop a watershed-wide standard. The development of the HMP began by preparing a Work Plan that was reviewed and accepted by the RWQCB followed by an in-depth literature review of the issues regarding hydromodification, methods of analysis, and potential management strategies. An Expert Panel of three university professors reviewed and commented on this work.

The permit requires a management plan that encompasses the full Santa Clara Valley Basin; however it is too costly to evaluate every stream system in the Basin. The Thompson Creek subwatershed was selected as a test watershed located in the south-eastern portion of the Basin (Figure 1). It is assumed that Thompson Creek will be representative of the entire eastern side of the Basin because the climate, physiography, soils and vegetation are similar.

The study area is 26 square miles upstream from a flow gage at Quimby Road, and includes five primary tributaries, which drain the east side Diablo Range (Figure 2). Historically, the tributaries did not directly connect to Thompson Creek, but discharged onto their alluvial fans, dropping any sediment load. Overland flow migrated north-westerly toward a natural topographic depression that is now Lake Cunningham infiltrating into the valley floor along the way. The study area has experienced rapid development in the last 25 years as agricultural land was converted to residential and commercial properties. During this period, the stream experienced rapid channel enlargement, including stream bed incision and bank failures. Local agencies designed and installed grade control structures in response to channel adjustments.

## LITERATURE REVIEW

This section provides a brief overview of the literature review as it pertains to the concepts of work and channel adjustment. Over 50 articles were reviewed that discuss: 1) the natural hydrologic and geomorphic process important to address hydromodification, 2) the effects of urbanization on hydrology and geomorphology, 3) assessment tools that can be used to address hydromodification, and 4) management strategies used to implement the HMP.

Early research in the 1970's showed that urbanization significantly alters the frequency and duration of natural runoff events especially for smaller more frequent storms (Hollis, 1975; Hammer 1972). Hollis (1975) concluded that the increase in runoff for flows with a frequency of 1 to 2-years and smaller, increased as much as 20 times. Flow changes of this type initiate long-term adjustments in stream morphology and channel enlargement is the most common response (Booth, 1990). MacRae et al. (1993) showed that increases in the frequency of the mid-bankfull to bankfull flow range caused the greatest increase in erosion. Bledsoe and Watson (2001) reported that the frequency of scouring events increased by factors of 2.5 to 5 for two watersheds they studied.

Booth (1990) suggested that stream power is a reasonable measure to distinguish between eroding and non-eroding channels. Stream power however, does not incorporate channel geometry or the boundary materials' ability to resist erosion, nor does it account for the duration that flows persist at these rates. Bledsoe and Watson (2001a) stated that the best indicators of stability involve a ratio of the erosive forces to the resisting forces. MacRae (1993, 1996) developed an index that includes a measure of the most sensitive boundary material's erodibility. MacRae (1993, 1996) suggested that the erosion potential for the channel boundaries should remain the same between developed and undeveloped land use conditions. A discharge control strategy that maintains the same erosion potential provides the closest reproduction of pre-development conditions and best protection of the stream's beneficial uses.

## STUDY APPROACH

The study is subdivided into five primary elements: 1) problem area and reach characterization, 2) geomorphic assessment, 3) hydrologic modeling, 4) stability assessment, and 5) effectiveness evaluation of solutions. Figure 2 presents a map of the study area and cross section locations where the analysis was performed.

Problem area and reach characterization describes features of the watershed and stream channels necessary to understand the nature and extent of the problem and to explain existing conditions. Historical aerial photography, soils and geologic maps, channel maintenance records, infrastructure data and historical surveys were used to distinguish between urbanizing impacts and impacts caused by past land use practices.

The geomorphic assessment describes the geologic and geomorphic characteristics of the stream network, the dominant physical processes that seem to be controlling stream attributes and erosion, and the extent and modes of failure for observed eroding channel banks and beds. Field crews recorded reach-wide observations on streambed and bank erosion, collected location specific data at 37 cross sections, and then assigned each location a rank of *stable, low, medium or high* observed condition of erosion, or likelihood of erosion in the near future. Several factors affecting channel bank and bed stability were combined with the extent, age, and magnitude of existing erosion to designate an appropriate erosion ranking.

A hydrologic continuous simulation model of the pre-project, existing, and future (year 2020) land use conditions was developed using the U.S. Army Corps of Engineers' Hydrologic Engineering Center - Hydrologic Modeling System (HEC-HMS). The model was calibrated using two years of measured flow data. The calibrated model was run using 50 years of rainfall record and produced a time series of hourly stream flows to analyze changes flow duration, runoff volume, and frequency between land use scenarios. The soil moisture accounting module was used to incorporate the affects of antecedent conditions.

The stability assessment is based on the premise that a balance among flow energy, sediment loads, and channel resilience exists naturally and should be maintained in order for the stream network to remain stable (GeoSyntec, 2002; McRae, 1996). The hypothesis is that, over time, the stream channel slope and geometry co-evolved with vegetation, local physiography and climate to establish its pre-development dynamic equilibrium. To maintain stream channel stability, the management goal is to maintain the pre-development flow energy, sediment transport and erosion characteristics.

An *index* representing the *total effective work* done on the channel boundary was derived that predicts the likelihood of channel adjustment given watershed and stream hydrologic and geomorphic variables. The index under urbanized conditions is compared to the index under pre-urban conditions expressed as a ratio (Ep). An empirical relationship between Ep and the observed channel erosion is derived and used to make informed decisions.

The effective work index ($W$) is computed as the excess shear stress that exceeds a critical value for streambed mobility or bank material erosion integrated over time and represents the total work done on the channel boundary:

$$W = C \cdot \sum_{i=1}^{n} (\tau_i - \tau_c)^{1.5} \cdot V \cdot \Delta t_i \qquad (1)$$

Where $C$ = constants and unit conversions, $\tau_c$ = critical shear stress that initiates bed mobility or erodes the weakest bank layer, $\tau_i$ = applied hydraulic shear stress, $\Delta t$ = duration of flows (in hours), and $n$ = length of flow record. The effective work index for presumed stable stream channels under pre-urban conditions is compared to stable and unstable channels under current urbanized conditions. The comparison, expressed as a ratio, is defined as the Erosion Potential (Ep) following McRae (1992, 1996).

$$Ep = \frac{W_{post}}{W_{pre}} \qquad (2)$$

where:

$W_{post}$ = work index estimated for the post-urban condition
$W_{pre}$ = work index estimated for the pre-urban condition

A "threshold of adjustment" is considered that distinguishes between stable and unstable conditions. The Ep and the threshold of adjustment are used to set management criteria and evaluate the effectiveness of proposed solutions (McRae, 1993).

## RESULTS

### GEOMORPHIC ASSESSMENT

The project team distinguished six hydrographic segments based on stream flows from large urban outfalls. Each segment has similar stream discharges and reflects important differences in channel flows. Table 1 lists the hydrologic and geomorphic conditions observed in the field.

*Channel Geometry and Slope*: Channel width and depth are extremely variable, with width generally differing by 4 to 5 times and depth by 2 to 3 times between cross sections. Segment 5 shows a rapid transition in channel geometry because changes from stable to unstable channel conditions are located within this segment. Channel slopes range by an order of magnitude (0.002 to 0.025 ft/ft) varying by cross-section throughout the reach.

*Bank Material*: Channel banks are not homogenous; instead they consist of multiple layers with different sediment characteristics that vary through the subwatershed. Thompson Creek is generally dominated by cohesive banks that are fairly resistant to erosion.

Segments of the creek have exposed hardpan in various locations. Layers of moderately to well-sorted sands and gravels with some silt and clay often represented the weakest portion of the bank. Widespread undercutting often occurred at the weaker alluvial layer.

*Bed Material*: The channel bed is generally composed of gravel with some sand. The median grain size (D50) ranged from 3.2 to 10.2 millimeters. The median grain size falls within the very fine to medium size gravel class. This allows use of the average critical shear stress and velocity for the bed. The average values for critical shear stress and critical velocity are 0.14 lbs/sq-ft and 2.8 ft/sec, respectively.

*Erosion Classification*: Erosion rankings of *stable, low, medium,* or *high* were assigned to each cross-section. These rankings were qualitative in nature and no numerical standard was applied. Instead, all factors affecting bank and bed stability (slope, undercutting, bank slope, type and density of vegetation, obstructions) were combined with the observed extent, age, and magnitude of observed erosion to designate the rank. Cross-sections that received a rank of *high* were severely incised reach-wide or actively incising with eroding banks, either through processes of undercutting, shearing and/or slumping. Channel banks were generally vertical and bare with vegetation stabilizing only the tops of banks. Eleven of the thirty-seven cross-sections were assigned *high*. Cross-sections designated as *low* had banks that were not eroded or eroded but now stable. *Low* ranking cross-sections generally had gentler slopes and denser vegetation, and sometimes located behind grade control structures where the bed had aggraded. Cross-sections ranked as medium had characteristics in between those described for *high* and *low*. Thirteen of thirty-seven cross-sections were designated as *medium* and thirteen designated as either *low* or *low* to *medium*. A rank of *stable* was assigned to three upstream sections.

STABILITY ASSESSMENT

Figure 3 presents a histogram of the pre-urban and post-urban flow records, which expresses the number of hours (i.e., flow duration) that flows occur within each discrete flow range. This figure shows that flow duration increases 2 to 3 times in the high flow range, and 20 to 30 times in the low flow range, between pre- and post- development scenarios. Runoff volume increases are also significant.

*Effective Work Curves*: Both incremental and cumulative work curves were generated and evaluated for both pre- and post-development. Figure 4 presents the cumulative curves for section TC1-6, in Segment 1 as an example. These curves illustrate which flows are doing the greatest amount of work on the stream channel and what flows have the greatest increase in work as a result of development. These results show that the greatest increase in work is done by flows less than the 2-year peak flow magnitude. Flows less than the 2-year peak flow magnitude have the greatest increase in frequency and runoff volume, and ultimately the greatest increase in energy to transport sediment and erode channel boundaries. These results also showed that approximately 95 percent of the total work is done by flows less than the 10-year peak flow magnitude. This information is used to target the appropriate flow range for management purposes.

**Table 1. Hydraulic & Geomorphic Characteristics of Thompson Creek**

| Cross-section | W/D Ratio[2] | Channel Slope | $D^{50}$ [3] | Exposed Clay Hardpan? | Depth of Mobile Material | Weakest Bank Material (left bank)[4] | Weakest Bank Material (right bank)[4] | Erosion Ranking (H,M,L)[5] |
|---|---|---|---|---|---|---|---|---|
| | *(unitless)* | *(feet/feet)* | *(mm)* | *(Y/N)* | *(in)* | | | |
| **Segment 1** | | | | | | | | |
| TC1-1 | 3.9 | 0.0016 | 5.8 | N | 24 | sandy gravel | silty loam and gravel | L |
| TC1-2 | 4.3 | 0.0040 | - | Y | 3-4 | silt loam | sand and small gravel | L |
| TC1-6 | 4.5 | 0.0102 | 4.5 | N | 12-24 | Sandy loam with gravel | gravelly sand | M |
| TC1-7 | 3.2 | 0.0091 | - | N | 12 | silt loam with gravel/sand | silty loam with gravel/sand | M |
| **Segment 2** | | | | | | | | |
| TC2-1 | 3.4 | 0.0078 | - | N | 18 | loamy clay | loamy clay | M-H |
| TC2-2 | 3.0 | 0.0160 | - | N | 10 | Clayey sand-gravel | clayey sand-gravel | L-M |
| TC2-3 | 3.5 | 0.0109 | - | N | 12 | Clayey sand-gravel | clayey sand-gravel | H |
| TC2-5 | 3.9 | 0.0117 | 4.0 | N | > 24 | silt, sand and some clay | sandy silt | M |
| TC2-6 | 4.0 | 0.0150 | - | N | 10 | well sorted med sand | clayey sand and gravel | M |
| TC2-8 | 3.5 | 0.0013 | - | N | 6 | Sand and gravel | fine sand | H |
| TC2-9 | 3.6 | - | - | N | 7 | colluvium | fine sand w/ some clay | L |
| TC2-10 | 4.5 | 0.0064 | 3.2 | N | - | sand-gravel-silt w/ clay | sand-gravel w/ some clay | M |
| **Segment 3** | | | | | | | | |
| TC3-1 | 4.3 | 0.0032 | - | N | 24 | sand | silty loam | L-M |
| TC3-2 | 5.6 | 0.0031 | - | N | 24 | silty-sandy loam | silty loam w/ pebbles | L |
| TC3-3 | 3.7 | 0.0045 | 5.0 | N | 24 | silty loam w/ gravel | silty fine gravelly loam | L-M |
| TC3-4 | 2.7 | 0.0084 | - | N | 24 | clayey pebbly with silt loam | sandy gravelly loam | M |
| TC3-5 | 5.3 | 0.0099 | - | N | - | silty sandy loam | gravelly silty loam | H |
| TC3-6 | 3.3 | 0.0086 | | Y | 24 | sandy gravelly loam | gravelly loam | H |
| TC3-7 | 3.8 | 0.0094 | 6.9 | N | 18 | silty loam with some gravels | silty loam with some gravels | L |
| **Segment 5** | | | | | | | | |
| TC5-1 | 3.9 | 0.0250 | - | N | 9.6 | sand and gravel with silt | silty sand w/ some gravel | H |
| TC5-2 | 2.7 | 0.0058 | 9.0 | N | >24 | silty sand and gravel | silty sand and gravel | M |
| TC5-3 | 1.5 | 0.0047 | - | N | 12 | Silts and sands | fine sand and silt | H |
| TC5-4 | 3.2 | 0.0166 | - | N | >24 | clayey sand and gravel | sandy silt | H |
| TC5-5 | 5.2 | 0.0102 | 3.7 | N | >>24 | Pebbly sand and silt | sand, pebbly sand | M-H |
| TC5-6 | 5.2 | 0.0086 | 8.0 | N | 12 | well sorted sand | sand and gravel | S |
| TC5-7 | 7.8 | 0.0129 | 3.5 | N | >24 | clayey sand and gravel | clayey sand and gravel | S |
| **Segment YB** | | | | | | | | |
| YB1-0 | 4.7 | 0.0222 | - | N | 24 | pebbly silty loam | pebbly silty loam | S |
| YB1-1 | 2.3 | 0.0179 | 10.2 | N | 12 | silty pebbly loam w/ gravels | silty pebbly loam w/ gravels | M |
| YB1-2 | 3.5 | 0.0282 | - | N | 12 | silty pebbly loam | silty pebbly loam | M |
| YB1-3 | 3.1 | 0.0221 | - | N | 24 | silty pebbly loam w gravels | silty pebbly loam | M |
| YB1-4 | 5.1 | 0.0111 | - | N | 24 | silty loam -- gravelly cobbly | gravelly cobbly loam | L |
| YB1-5 | | - | - | Y | 12 | cobbly, silty, pebbly loam | cobbly, silty, pebbly loam | L |
| YB1-6 | 1.2 | 0.0139 | | Y | 12 | clay-silty gravelly-cobbly | clayey-gravelly loam, silty | H |
| YB1-7 | 11.0 | 0.0149 | 4.8 | N | 24 | silty gravelly loam | silty gravelly loam | M |

*Erosion Potential (Ep)*: Figure 5 presents an Erosion Potential Chart with Ep plotted for each section sub-divided by the field designated erosion classification. Only a subset of the results is shown for clarity. There is a good correlation between the observed erosion classification and the magnitude of the computed Ep. An Ep ratio of 2 means that the post-urban runoff condition exerts 2 times more total work on the channel boundary then under the pre-urban condition. Ep ratios range from less than 1 to 10. Interestingly, some sections that fall below Ep=1 were observed in the field as potentially aggrading.

One of the objectives was to identify a *threshold* that could be used to define management strategies and discharge limitations. Figure 6 presents a probability curve using a Logistic Regression technique on the data presented in Figure 5. This technique relates the probability of having unstable channel conditions to the computed Ep (Bledsoe and Watson, 2001b). For example, given a computed Ep of 2, the likelihood of having unstable conditions is about 20 percent. The probability curve can also be used to select an Ep threshold by specifying a level of acceptable "risk" (i.e., probability that a stream channel is not stable). For example, to accept a 10% "risk", the Ep threshold would be 1.2. The effectiveness of management strategies and BMP's are evaluated by their ability to maintain the Ep below the threshold of 1.2.

MANAGEMENT STRATEGIES

Stormwater management strategies that were considered include pre- and post- runoff volume matching, hydrograph matching, flow duration matching, and managing effective work through the erosion potential (Ep). Various combinations of BMPs can be used including on-site or project based controls, larger scale regional controls, and in-stream controls that modify the stream to accept the changed watershed hydrology. Results to date indicate that flow duration matching is a protective management strategy that can apply to on-site or project based controls which has the benefit of not requiring additional information on instream hydrology and stability. Ep control is more applicable to watershed wide master planning involving regional and instream controls and possibly for very large developments.

It was originally thought that practical implementation could be achieved by allowing smaller developments to perform simpler calculations, such as discrete event volume control or hydrograph matching. However, after further study, the simpler methods are not proving to be adequate to protect stream channels from hydromodification because of the cumulative nature of smaller but erosive flows.

Volume control means that only the amount of runoff generated from the pre-urban site may be discharged from the site after development, and the difference in volume must be retained on-site or discharged to some other out-of-stream facility such as a by-pass. Our analysis found that specifying volume control alone would not be protective and could lead to increases in work and stream erosion. This is because post-urban runoff is discharged at higher rates of flows due to increases in impervious surfaces. Volume control alone does not account for the differences in erosive power for the same volume at higher flows as compared to lower flows.

To improve volume control, one management approach would be to require "hydrograph matching". Hydrograph matching maintains the volume and distribution of flows for a single discrete storm event (e.g., the discharge from the flow control facility for, say, a 10-year storm must match the pre-development runoff hydrograph shape and volume for that storm). Hydrograph matching was tested by designing a control basin to maintain the design event hydrograph shape and volume and then evaluating the basin's effectiveness at maintaining the pre-urban work. Design storms used included the 2-, 10-, and 50-year hydrographs. The analysis found that hydrograph matching would not adequately maintain the in-stream erosion potential for the full range of flows.

Flow duration control is an extension of volume control but is more accurate for sizing controls because matching flow duration maintains runoff volume for the full distribution of flows. When one matches the pre-urban flow duration curve, the total number of hours that flows persist at any given magnitude is maintained and thus work is maintained. Flow duration control can be used on-site or for mixed regional solution strategies. Flow duration control was found to be effective at maintaining the erosion potential of the stream.

Although flow duration control is an effective management strategy, a more comprehensive approach is to perform an Ep analysis and directly compute the erosion potential in-stream. In addition to evaluating hydrologic modifications, the Ep method can be used to distinguish between more or less resilient stream channels, identify critical stream reaches, and used to design in-stream solutions that modify channel characteristics to accept the new hydrologic regime.

The Ep methodology was used to test the effectiveness of in-stream modifications and found to be a good tool for designing effective restoration projects. The Ep methodology can measure the effect of changing channel slope, geometry, roughness, and resistance from armoring (e.g., biotechnical solutions). The Ep method predicted stable slopes consistent with the results using regime equations and with measured slopes in undeveloped watersheds around the Bay Area. Biotechnical solutions can substantially increase the apparent critical shear stress of the channel boundary from 0.14 lbs/sf to 1.6 lbs/sf or larger, and the Ep can be reduced to within the threshold of 1.2.

## CONCLUSIONS

All conclusions specifying a numeric value apply to Thompson Creek and the eastside Santa Clara Valley, and would not necessarily apply to other watersheds outside this region.

1. Hydromodification and associated channel enlargement are best addressed as the long-term cumulative process of frequent erosive flows, as opposed to using discrete event methods.
2. Urbanization significantly increased the duration and erosion potential of small to moderate size flows more than those for larger flows. The incremental work associated with geomorphically significant flows for post-urban conditions exceeds the pre-urban case by as much as 20 to 30 times.
3. The effective work index (*W*) distinguishes between stable reaches (pre-urban, stable/low existing conditions), and unstable reaches (medium/high existing conditions).
4. The Ep Chart and Logistic Regression show a strong indication of a *threshold of adjustment* and express the likelihood or "risk" of channel instability from hydromodification. An Ep threshold of 1.2 is associated with a 10 percent likelihood of causing stream channel erosion and enlargement. An Ep threshold of 1.2 has been selected for effectiveness tests, management and designs.
5. The Ep methodology is best used to address cumulative watershed scale modifications in land use and hydrology during master planning or for larger scale development projects.
6. Ep can be used to evaluate the effectiveness of hydromodification management strategies, including on-site, regional, in-stream projects, or a mix of strategies.
7. Matching runoff volume or design storm hydrographs for single events, such as the 2-year event, is not protective of streams at risk from hydromodification, and should not be used as management strategies.

8. Matching pre- and post-urban flow duration curves is the best management strategy for design of on-site and regional BMP's when limited watershed or stream hydro-geomorphic data are available.

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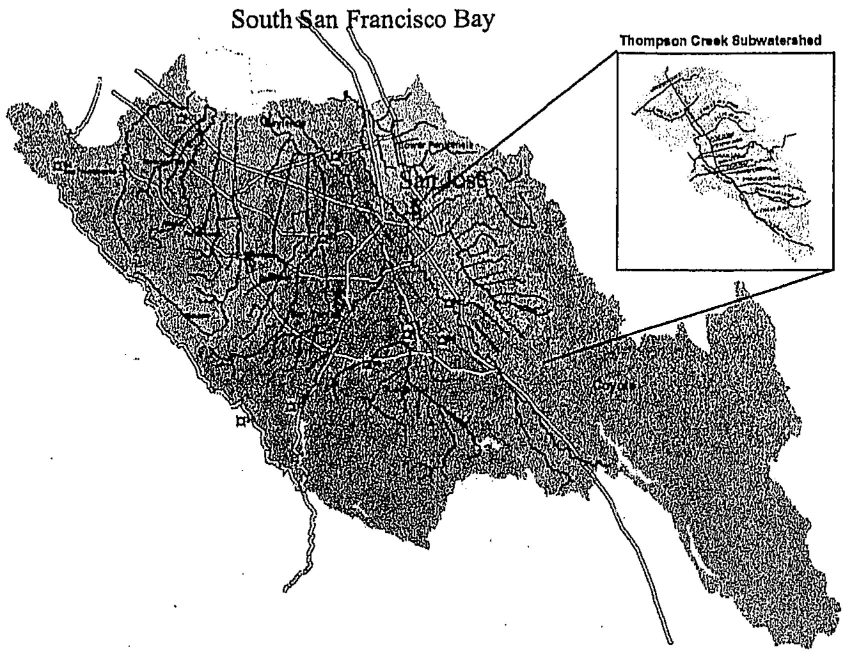


**Figure 1. Santa Clara Valley Basin and Thompson Creek Study Area**

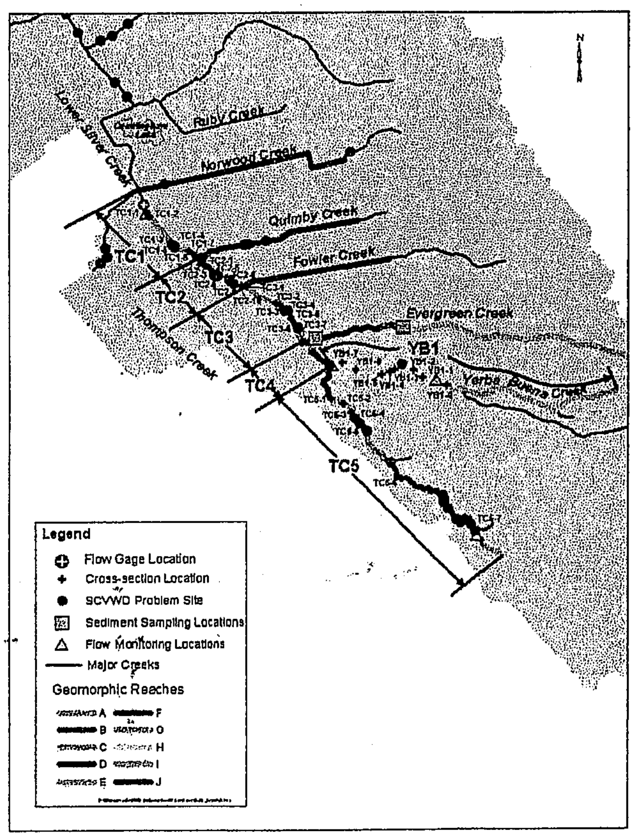


**Figure 2. Thompson Creek Study Area Characteristics**

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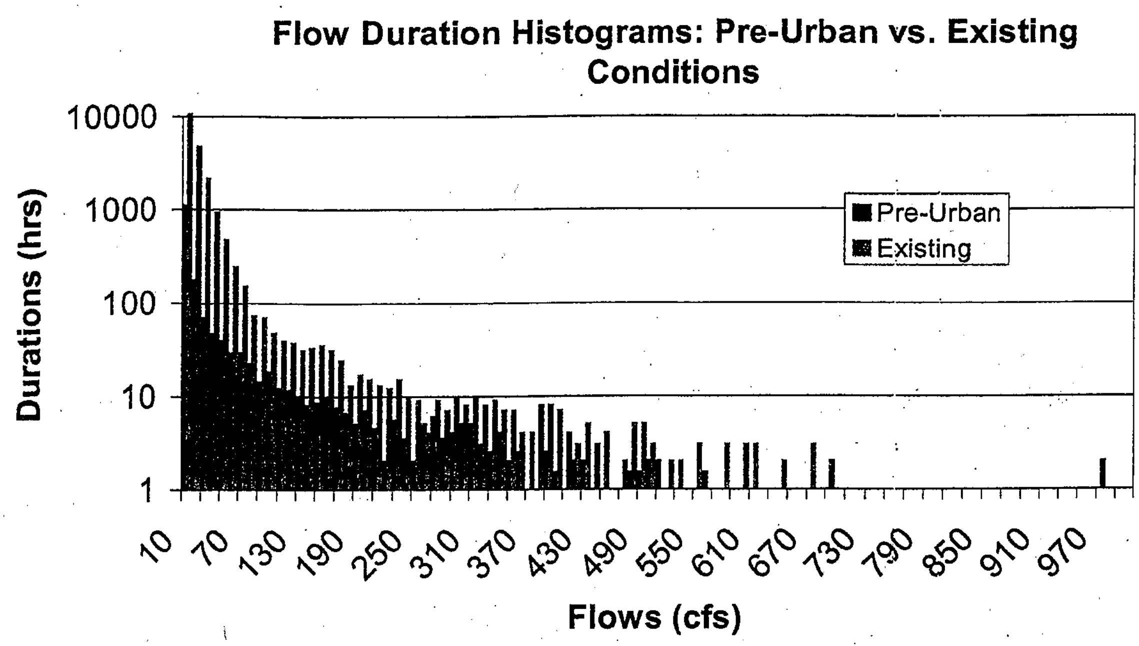


Figure 3. Histograms for pre-urban and existing conditions

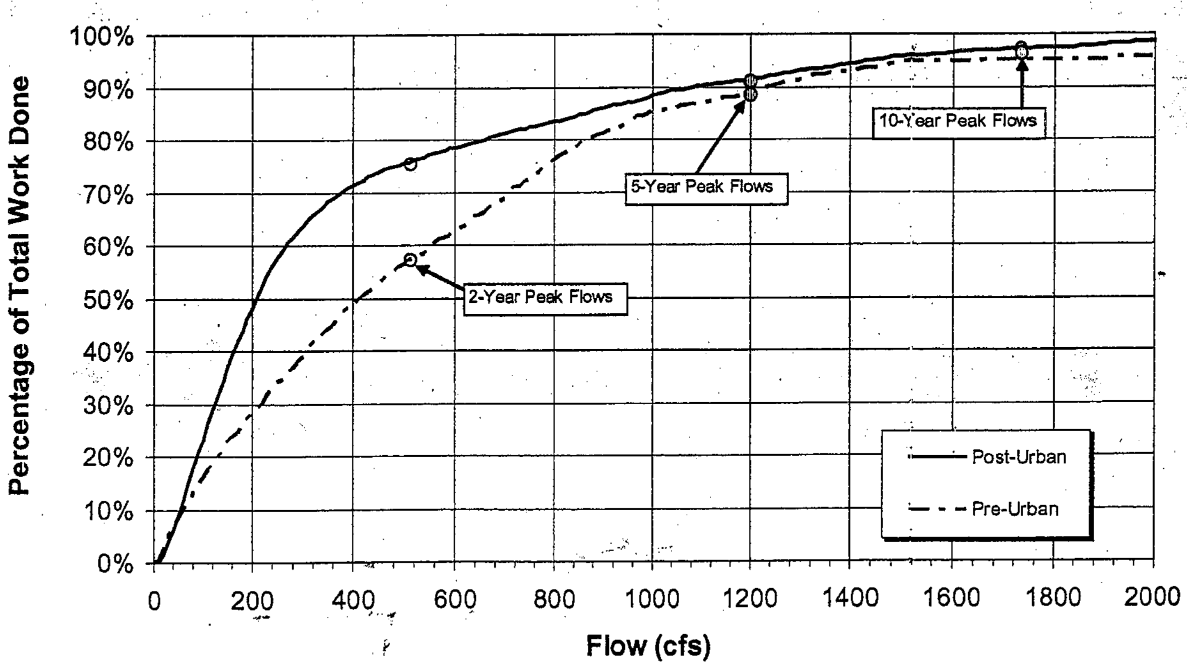


Figure 4. Cumulative Work Curves for Segment 1, TC1-6

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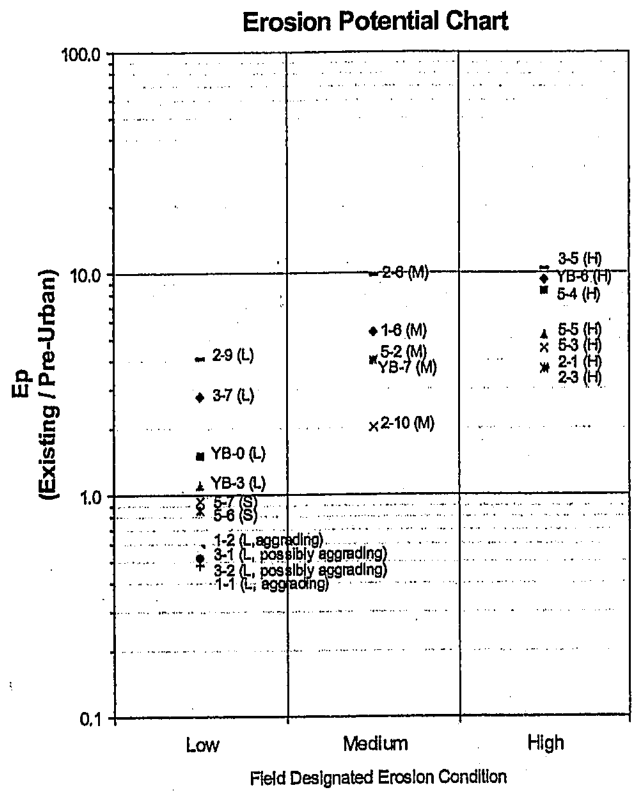


**Figure 5. Erosion Potential Chart illustrating Ep for each cross-section based on erosion classification (low, medium and high)**

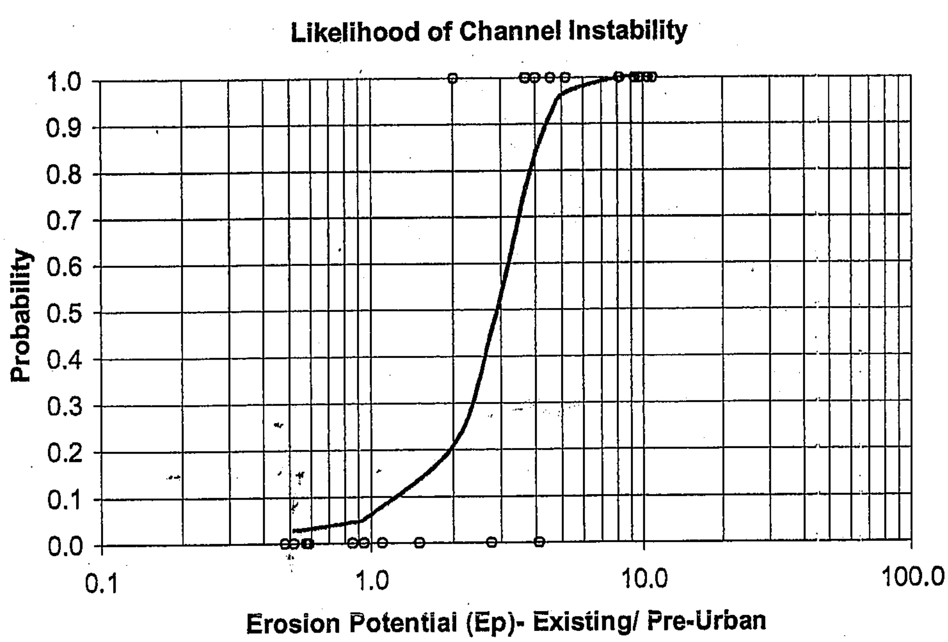


**Figure 6. Probability curve of the Ep using a Logistic Regression**

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# RELIABILITY OF DESIGN STORMS IN MODELLING

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**Abstract.**

Stormwater runoff is generally simulated using a design storm as input. The use of design storms significantly reduces the complexity of stormwater runoff analysis. As a result, the use of design storms is popular among engineers. The basic premise behind their use is that a design storm of a given return frequency will produce a simulated runoff peak and volume having the same return frequency. As an example, using a 5-year design storm will result in a 5-year runoff peak and volume.

Typically, design storms are developed by statistical analysis of rainfall records. The resultant temporal distributions of these design storms may be quite unlike the rainstorms occurring in nature. Worse, the use of design storms may not be resulting in runoff peaks and volumes having the same return frequency. As a result, drainage and flood control facilities designed using design storms may be oversized or undersized. Unfortunately, design storms are, by and large, not tested against long-term rainfall/runoff record simulation to determine if they will reasonably simulate runoff for a given return frequency.

A research effort is underway by the Urban Drainage and Flood Control District in the Denver, Colorado area to develop more reliable runoff simulation techniques. As a part of this effort, the design storm concept is being analyzed. Although the District's research effort is broad in scope and is exhaustive in nature, this paper discusses only the findings and the work to date relative to the design storm concept. The findings are based on applying 73 years of rainfall to simulate runoff with computer models. These computer models were calibrated for each catchment using rainfall/runoff data collected since 1969. In addition, this paper examines the principles of design storm analysis and offers suggestions on how to develop and test design storms.

## Introduction

In 1969 the Urban Drainage and Flood Control District (District) serving the metropolitan Denver, Colorado, area, became a cooperative sponsor with the U.S. Geological Survey (USGS) to collect rainfall/runoff data from urban catchments. In 1977 the District started its own data analysis and research effort to develop more reliable urban runoff simulation techniques. As a part of this effort, the design storm concept was analyzed. Although the District's research efforts are broad in scope, this paper presents only the recent findings related to the design storm concept.

## Background

The use of design storms is very popular among drainage and flood control engineers and has achieved almost universal acceptance. In practice, it is assumed that a design storm of a given recurrence frequency will simulate a runoff peak and volume having the same frequency. Several techniques to develop the design storm from rainfall records have evolved or have been proposed over the past 20 years, including Chicago[1], ISWS[2], CUHP[3], and Urban Storm Runoff Inlet Hydrograph Study[4]. All of these techniques are based on the statistical analysis of rainfall data with very little, if any, verification of results through the investigation of the resultant runoff. Since only rainfall data are analyzed, independent of the total rainfall/ runoff process, the validity of the design storm concept has been questioned. McPherson[5] has pointed out the fallacy of assigning identical frequencies of occurrence to rainfall and runoff when in reality both processes can exhibit statistical non-homogeneity. The use of the design storm, according to McPherson, may be acceptable when only gross differences in level of protection from flooding are sought, but actual rainfall histories need to be used for the final design of operating facilites.[6]

Recent investigations have reported differences in predicted recurrence probabilities of peak flows using design storms when compared to simulated peaks using actual rainfall histories[7,8,9]. Marsalek observed that for the conditions he investigated in Ontario, Canada, only half of the linear variation in runoff peaks could be explained by the linear variation in rainfall intensity . This led him to conclude that parameters of rainfall distribution are important in the generation of realistic runoff peak flow. Wenzel and Voorhees concluded that the design storm hyetograph and antecedent soil moisture conditions are very important parameters9. Both Marsalek and Wenzel expressed concern about the validity of the computer models used when extrapolating to less frequent large storm events. Both reported their models operated in a surcharge mode during the larger events and, as a result, they felt the accuracy of the predicted runoff peaks during very large rainstorms was suspect.

## Rainfall Analysis

Local governments in the Denver area have adopted the use of t e Urban Storm Drainage Criteria Manual (USDCN)3 for planning and design of drainage and flood control facilities. The manual was published in 1969 by the Denver Regional Council of Governments (DRCOG) and contains rainfall isopluvial maps for the Denver metropolitan area for a variety of storm duration and return periods. The USDCM also contains a step by step procedure for reducing the isopluvial information to design storms. Subsequent to the adoption of the USDCM by local governments, another set of isopluvial maps was published by the National Oceanic and Atmospheric Administration (NOAA)10. The two sets of maps did not agree. The local governments continued to use the previously adopted USDCM rainfall information, while Federal agencies used the NOAA Atlas. Occasionally, disagreements occurred between various parties that were based solely on the argument that one set of design storms was better than the other. None of the arguments were backed by runoff data.

To examine the validity of the published isopluvial maps, the 73 maximum 30-minute rainfall depths recorded at the Denver gage from 1898 through 1971 were reduced to a Weibult probability plotting position. The rainfall data plotted on log normal probability paper are shown on Figure 1. The two lines shown on Figure 1 show the 30-minute rainfall depths obtained from the DRCOG and NOAA isopluvial maps. It is interesting that neither of them fit the rainfall data well, yet the isopluvial maps information was the basis of disagreements between local and Federal officials. If one thoroughly investigated the procedures used to develop the two sets of isopluvial maps, the reasons for these differences can probably be discovered. However, that is not the point. What is important to recognize is that published rainfall depth-frequency-duration maps are often used as the basis for development of design storms. Besides being statistically nonhomogeneous with runoff, the design storms in themselves may originate from information that may not be totally consistent with the rainfall data collected locally.

Also shown on Figure 1 are the 7-day antecedent precipitation data corresponding to each of the rainstorms used. Examining this data reveals that the antecedent precipitation is random in nature and it is not possible to draw any conclusions as to how it may affect the statistical distribution of runoff. To identify the potential effects of antecedent precipitation, it is necessary to examine the runoff peaks simulated while accounting and not accounting for antecedent moisture conditions. Such dual runoff simulation was performed and the results are reported later in this paper.

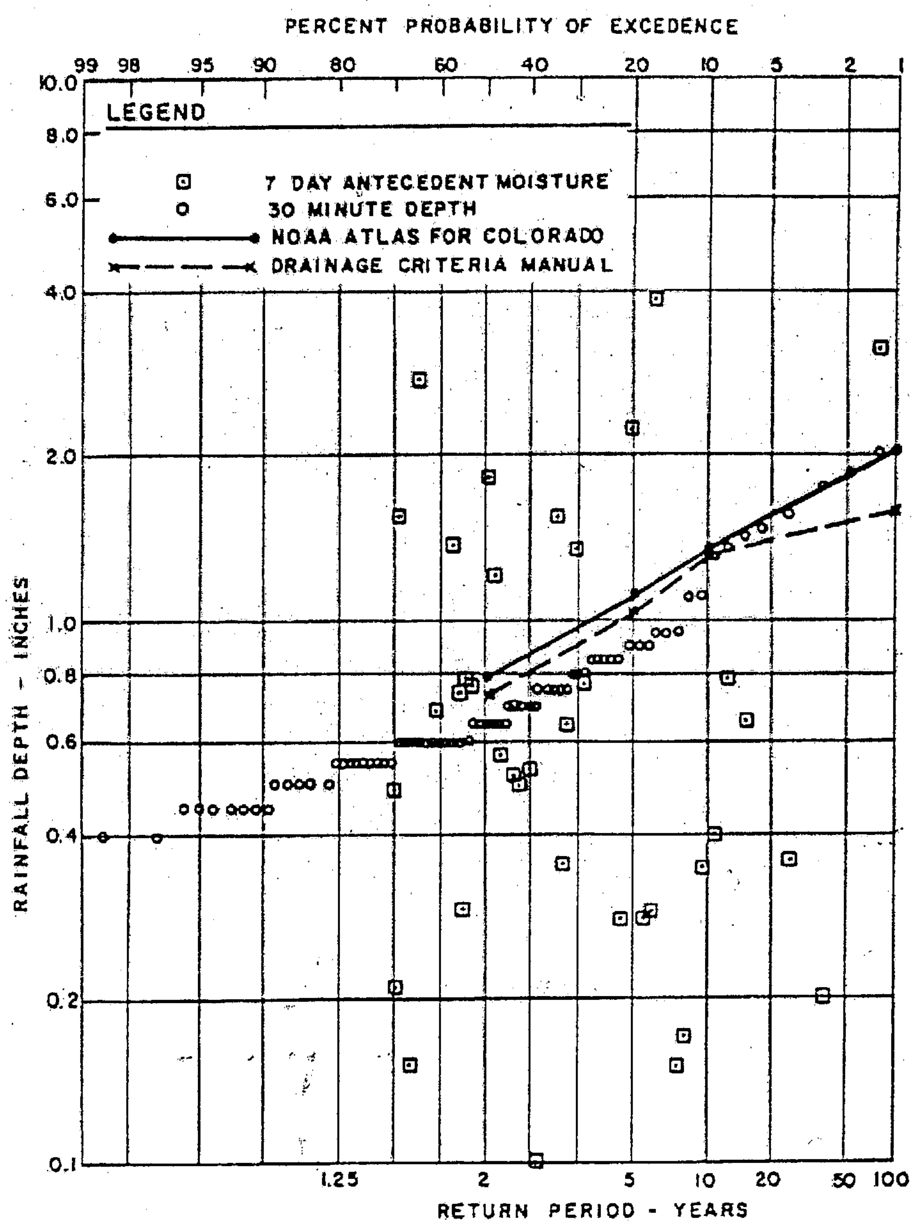


Figure 1. Probability Distribution Of 30-Minute Rainfall Depths at Denver Raingage, 1898 through 1971.

## Runoff Analysis

*Gauging Program*

Shortly after its inception in 1969, the cooperative District and USGS rainfall-runoff data collection program set up approximately 30 gauging stations in the Denver metropolitan area. In 1977 the District started its own data analysis and interpretation effort. After a review of the data collected, approximately one-half of the gauging sites were abandoned and the data collected at these sites were dropped from the records because of problems ranging from variable catchment boundaries to flow gage rating curves that could not be defined. It is difficult to interpret field data obtained even under perfect gauging conditions and the additional difficulties associated with the interpretation of questionable data was sufficient reason to limit data acquisition and analysis to sites where problems could be identified and resolved.

Seven of the stations remaining in the data collection program have been analyzed in detail to date. Of these seven, data from four of the catchments were chosen for use in the investigation of the design storm concept. The four catchments represent a variety of urban land uses, including a mobile home park (Northglenn site), single family residential (Denver and Englewood sites), and an airport terminal. Site maps for each catchment are shown in Figures 2 through 5. Catchment Characteristics for all four are summarized in Table 1.

Table 1. Observed Characteristics of Gauged Catchments

| | Area (mi2) | Length (mi.) | Slope (ft/ft) | Impervious (Percent) | Drainage System |
|---|---|---|---|---|---|
| 1. Northglenn | 0.56 | 1.17 | 0.034 | 35 | Streets and Grass Channel |
| 2. Denver | 0.29 | .84 | 0.005 | 40 | Streets and Concrete Channel |
| 3. Englewood | 0.43 | 1.52 | 0.010 | 45 | Streets and Pipes |
| 4. Airport | 0.15 | .97 | 0.005 | 97 | Large Pipes |

The first three catchments were selected for this study because the stormwater runoff is not subject to detention storage routing of any kind within the catchments. There is a possibility of flow surcharge storage at the airport site during rainstorms having a recurrence interval in excess of ten years; however, none of the gauged runoff events indicated a surcharged condition. Although the simulated runoff from the airport site may not accurately reflect the true Probability for recurrence intervals greater than ten years, all four sites can be considered to indicate runoff trends from sites that have no on-site detention storage.

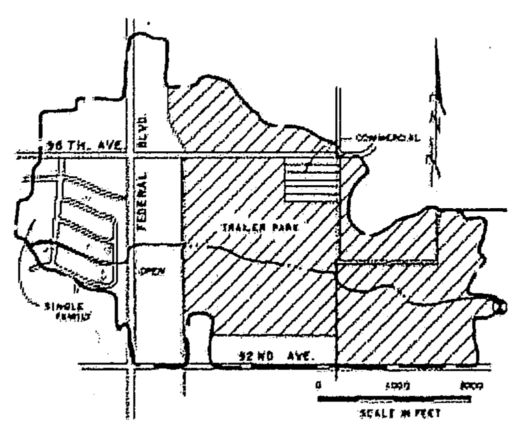


Figure 2. Map of the Northglenn Site

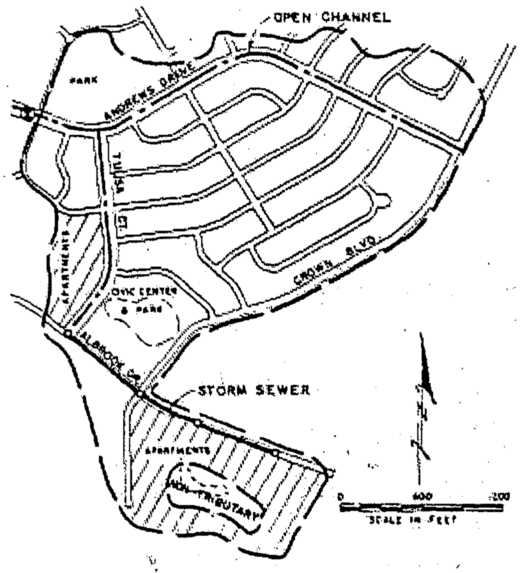


Figure 3. Map of Denver Gauging Site

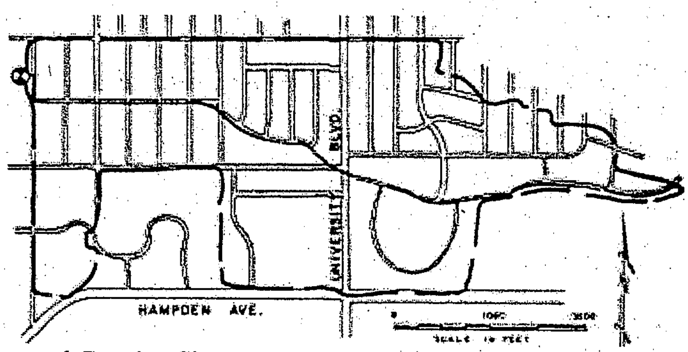


Figure 4. Map of Englewood Gauging Site

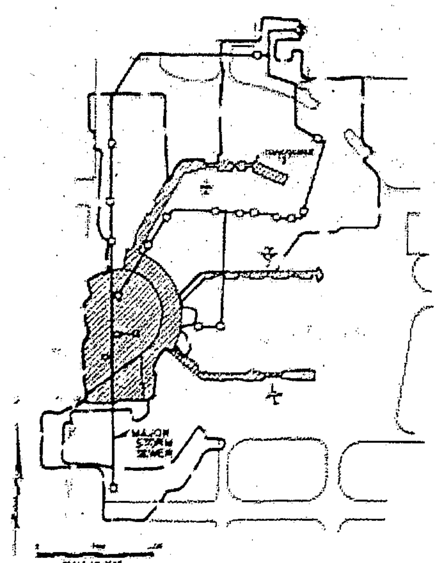


Figure 5. Map of Airport Gauging Site

*Model Calibration*

Runoff simulation was performed using the District's computer model calibrated for each site. The model uses a linear unit hydrograph in combination with Horton's exponential decay infiltration function.[11] This model was selected for its simplicity and low cost of operation. In addition, after it was calibrated, it reproduce the gauged runoff peaks and volumes consistently. The model was calibrated to match runoff peaks and volumes using the rainfall and runoff data recorded at each of the four gauged catchments. Two kinematic wave models were also calibrated for the Denver site, but they produced less consistent duplication of runoff peaks and were considerably more difficult to use in processing large numbers of storm events. As a result, neither kinematic wave model was used for this investigation.

Table 2 summarizes the calibrated infiltration and other rainfall losses used in the runoff simulations. The data for the four sites were analyzed in detail to gain insight into the effects of antecedent precipitation. Based on what was learned, the initial infiltration and depression storage values were adjusted for each storm to compensate for the effects of the recorded antecedent precipitation data. A comparison of the observed and simulated flow peaks at all four gauging sites is shown in Figure 6, which also demonstrates the validity of the computer model calibration.

Table 2. Calibrated Rainfall Loss Parameters

| Gauging Site | Initial Infiltration (in/hr) | Final Infiltration (in/hr) | Exponential Coefficient (1/sec.) | Pervious Storage (in.) | Impervious Storage (in.) |
|---|---|---|---|---|---|
| 1. Northglenn | 3.00 | 0.50 | 0.0018 | 0.50 | 0.10 |
| 2. Denver | 4.50 | 1.10 | 0.0007 | 0.40 | 0.10 |
| 3. Englewood | 4.00 | 0.50 | 0.0018 | 0.40 | 0.10 |
| 4. Airport | 3.00 | 0.50 | 0.0018 | 0.40 | 0.10 |

Having a calibrated computer model for each of the four gauged catchments, it was possible to simulate the runoff that would result from a series of large rainstorms recorded at the Denver rain gage. Digitized rainfall data for a 73-year period (1898-1971) at the Denver rain gage were obtained by USGS from :he National Weather Service. The 73 rainstorms having the largest recorded one-hour rainfall accumulation were selected to represent a partial duration series for the 73-year period of record. Because the digitized rainfall data was reported in 5-minute time intervals, and because the study catchments were relatively small, a 5-minute unit hydrograph was selected for use in this study.

All 73 storms were used to simulate peak stormwater runoff from the four sites. Before the long-term simulation was started, the antecedent precipitation for each of the 73 storms was quantified and initial rainfall abstractions were adjusted using the trends observed from the rainfall/runoff data at the gauged catchments. A total of 73-runoff peak flows were then simulated and analyzed using the Log Pearson Type III statistical analysis recommended by the U.S. Water Resources Council.[12] An identical statistical analysis was performed using peak flows simulated while ignoring the effects of antecedent precipitation. The resultant Log Pearson Type III distributions of the simulated peak flows vs. their recurrence period are presented in Figures 7 through 10.

Antecedent precipitation appears to have a relatively small effect in the four test catchments. It is possible that the algorithm used in correcting for antecedent precipitation underestimated its effects; however, there are other possible explanations. Denver is located in a semi-arid region of the United States and has an average annual precipitation of only 15 inches, with approximately one-half of that being rainfall. Referring to Figure 1, one can see that only ten of the 73 rainstorms shown had a 7-day antecedent rainfall that exceeded 0.8 inches. The lack of precipitation in this semi-arid region also results in the lack of antecedent precipitation and can explain why it has only a minor effect on the statistical distribution of runoff peaks.

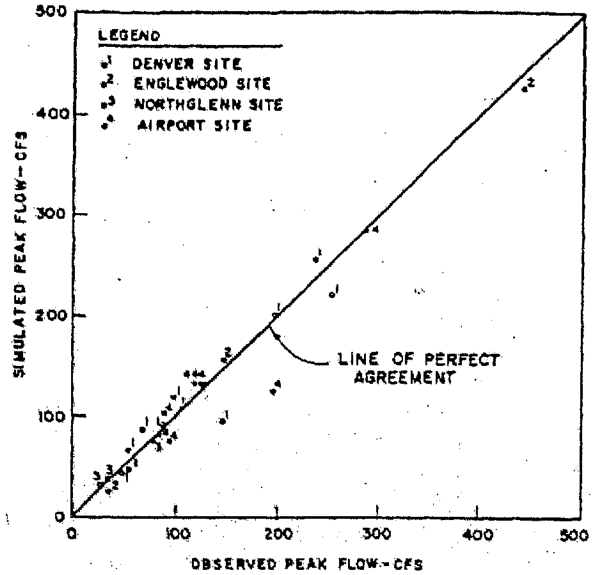


Figure 6. Comparison of Simulated and Observed Peak Flows

The District's studies also indicate that the runoff from impervious surfaces in the Denver area tends to overshadow the runoff from the pervious areas. Runoff from impervious surfaces is very quick to occur and concentrate and is primarily responsible for the peak flow on small urban catchments. At the same time, runoff from pervious areas occurs later in the storm and contributes little to the peak flow during the storms that are common to the semi-arid climate. High antecedent moisture may result in increased volumes, but it appears to have very little impact on peak flows from urbanized catchments in the Denver area and possibly in other communities located in the semi-arid regions of the country.

To illustrate the relative accuracy of the two types of design storms being used in the Denver area, the peak flows estimated using the design storms are also shown in Figures 7 through 10. These design storms were developed in accordance with the USDCM procedures and the DRCOG and NOAA published isopluvials discussed earlier. It appears that using design storms developed solely from rainfall data can result in significant variances in the peak flows when compared to the statistical distribution of simulated peaks.

The predominant trend is for the tested design storm to overestimate the peak flow. This is not surprising since the statistical analysis commonly used in the development of design storms tends to maximize rainfall depths for all time increments. However, the author believes that the temporal distribution of the design storm can also affect runoff peak calculations. When a leading or advanced type of design storm distribution is used, the largest rainfall intensities occur at the time when rainfall losses are large and the runoff is reduced. If, however, a lagging storm pattern is used, the reverse is true and runoff is increased.

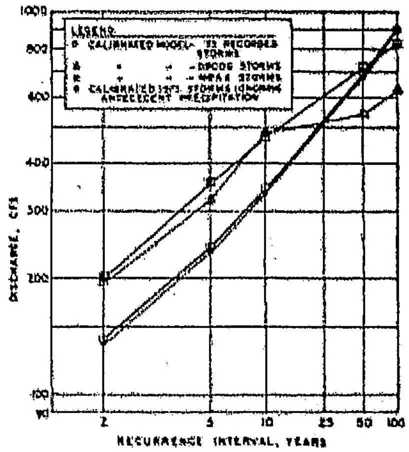


Figure 7. Peak Flow Probability Distribution for Northglenn Site

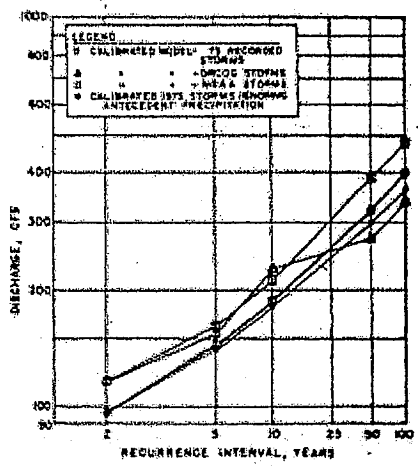


Figure 8. Peak Flow Probability Distribution for Denver Site

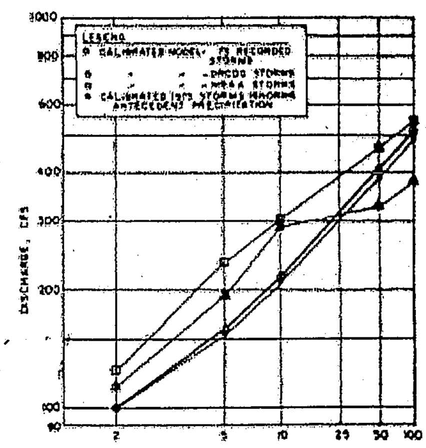


Figure 9. Peak Flow Probability Distribution for Englewood Site

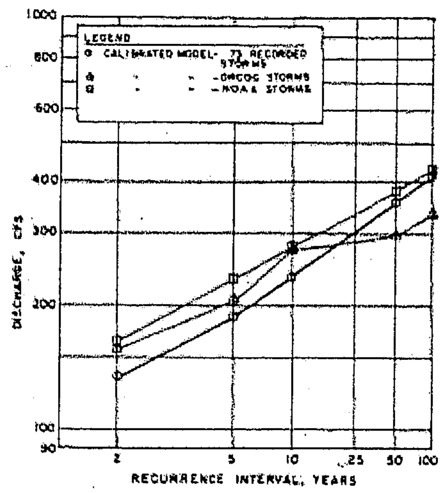


Figure 10. Peak Flow Probability Distribution for Airport Site

Because of the random nature of the temporal distribution of rainfall during rainstorms, it is naive to believe that a design storm can be developed to represent a real storm of a known recurrence interval. Design storms do not represent typical rainstorms and are a conglomeration of many storms that have occurred in the past. However, the concept of a design storm should not be abandoned just because a design storm does not represent a typically occurring rainstorm. A properly conceived design storm can still be a very valuable planning tool for use in estimating rainstorm runoff, provided its shortcomings are understood and it is used only when appropriate.

## Alternatives to a Design Storm

What alternatives are there to a design storm? One obvious alternative is to perform a long term simulation using a calibrated computer model and recorded rainfall data. This approach would be similar to the one taken during the District's investigation and may be more accurate. Such an approach takes substantial expertise, time and budget. Another alternative is to identify a number of recorded rainstorms , say five to ten, as being representative of a desired recurrence event which can be used to test final design of drainage facilities. The advantages of this approach include the use of recorded rainfall data, which accounts for a number of temporal distributions found in nature, and the user is provided with the argument that an arbitrary design storm is not being used. The use of select recorded storms has disadvantages that are similar to the ones stated for the long term simulation method, without the advantages of using a complete rainfall history. Regardless of how the historic rainfall record is used, it is important to recognize that it is a historic record and is not an absolute predictor of the future.

When the planning effort has substantial potential economic impact, is regional in nature, and a high level of expertise and adequate budget can be committed, then long term simulation is justified and needs to be considered. For instance, regional non-point source water quality planning is an area where the design storm approach has very little merit. The non-homogeneous statistical characteristics of rainfall, antecedent precipitation, pollutant buildup rates, best management practices, and other phenomena, some of which are not well understood at this time, demand that a rainfall record of temporal and spatial distribution be used. Similar arguments can be made for regional flood control planning. However, when the problem shifts to smaller drainage sub-catchments and individual storm sewer or detention pond design, there is a need for simplified approaches to the problem. In such instances the design storm is state-of-the-art to many of the professionals.

## Design of a Design Storm

The Urban Drainage and Flood Control District have recognized the need for a simple, straightforward, approach in urban drainage and flood control field. This need prompted the District to pursue the development of design storms that would simulate peak flows to fit the runoff probabilities. The approach required the use of readily available published rainfall information that had a broad base of acceptance. Because the NOAA Rainfall Atlas[10] was used by the State of Colorado outside the District and was exclusively in use by Federal agencies, it was selected as the base source of rainfall information. The one-hour rainfall depths for the various recurrence intervals were taken from the Atlas at the Denver Rain Gage location. A temporal rainfall distribution was then developed for each recurrence interval storm and was converted to a percentage of the NOAA Atlas one-hour rainfall depth. After several runoff simulation trials a series of temporal rainstorm distributions related to the NOAA Atlas information were found to reasonably reconstitute the peak at each recurrence interval for all four test catchments. The results can be seen by comparing the peak flows, obtained using the new design storm, against the distribution curves of the peak flows, obtained using long-term simulation. The comparisons are made in Figures 11 through 14.

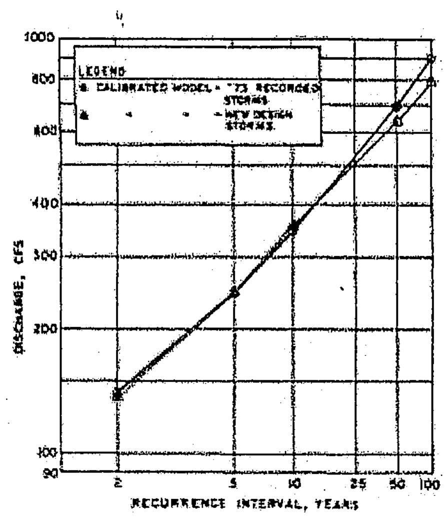


Figure 11. Peak Flow Distribution Using New Design Storms for Northglenn Site

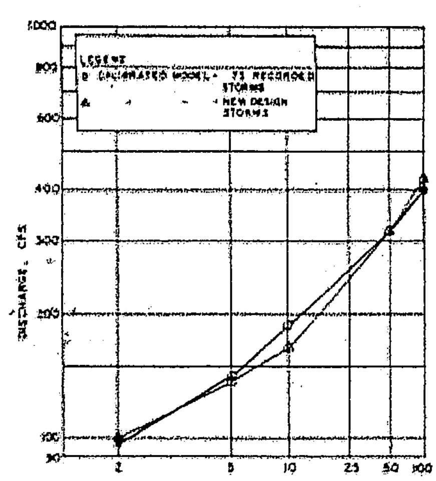


Figure 12. Peak Flow Distribution Using New Design Storms for Denver Site

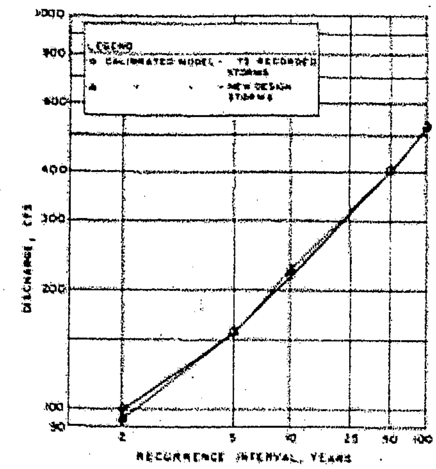


Figure 13. Peak Flow Distribution Using New Design Storms for Englewood Site

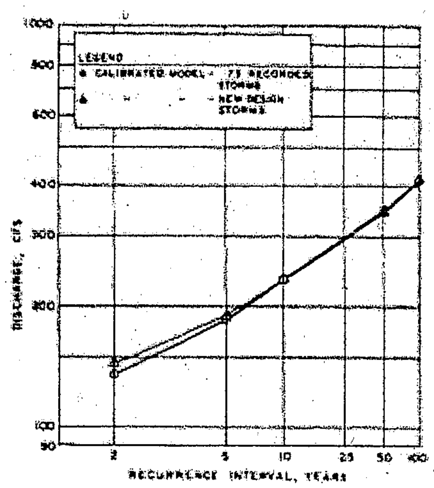


Figure 14. Peak Flow Distribution Using New Design Storms for Airport Site

The results to date look encouraging; however the District is not yet prepared to revise the USDCM. Before permanent policy revisions are made to the design procedures used in the Denver area, the new design storms will undergo further testing using other gauged catchments. The volumetric integrity of the hydrographs simulated using the new design storms also needs to be verified. Flood routing of the hydrographs obtained using the long term rainfall record will be performed using a variety of detention pond designs The routed peaks will then be statistically analyzed and compared against routed peaks obtained using the new design storms. It is hoped that the new design storms will have realistic flood routing characteristics. If they don't, it may even be necessary to develop another series of design storms for use in the design of detention storage facilities. The ultimate goal of the District is to develop design storms that will consistently result in a reasonable prediction of the peak flows and volumes for storm runoff in the Denver area. These design storms will then be available to the engineering profession for use in the design of local drainage and flood control facilities. These new design storms are not intended to be used in regional non-point water quality studies, nor professed to be the only ones to be used in regional flood control projects.

## Summary and Conclusion

The Urban Drainage and Flood Control District staff is involved in a research program to develop more reliable urban stormwater runoff simulation tools. As part of this effort, the District is investigating the design storm concepts being used in the Denver area. As a result of this investigation the following observations and conclusions have been made:

1. Design storms are developed using information contained in published isopluvial maps that may not be totally consistent with the long-term rainfall data collected locally.

2. Design storms developed using published isopluvial maps result in runoff peaks that can vary significantly from the peak flows obtained through statistical analysis of long-term simulation of runoff using recorded rainfall.

3. Antecedent precipitation in the semi-arid Denver area appears to have very little effect on the probability distribution of runoff from small urban basins.

4. It is possible to develop. design storms that reasonably duplicate the peak flows from small urban basins at various recurrence intervals. However, this requires substantial rainfall/runoff data to permit calibration of computer models, long term simulation of runoff using recorded rainstorms and statistical analysis of simulated flow peaks and volumes.

5. Design storms developed using long term runoff simulation as a point of reference are useful in the planning of storm sewers, detention ponds and other flood control facilities. Recorded rainfall records that include temporal and spatial rainfall distributions need to be developed and cannot, at this time, be short cut through the use of a design storm whenever water quality studies are performed and/or stormwater management operational systems are designed. The use of design storms for these purposes fails to recognize the non-homogeneous statistical distribution of a large number of variables affecting the results.

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# Illicit Discharge Detection and Elimination

*A Guidance Manual for Program Development and Technical Assessments*


by the
Center for
Watershed Protection

and
Robert Pitt
University of Alabama


October 2004

# Notice

The information in this document has been funded wholly or in part by the United States Environmental Protection Agency under cooperative agreement X-82907801-0. Although it has been subjected to the Agency's peer and administrative review, it does not necessarily reflect the views of the Agency, and no official endorsement should be inferred. Also, the mention of trade names or commercial products does not imply endorsement by the United States government, the Center for Watershed Protection, or the University of Alabama.

# ILLICIT DISCHARGE DETECTION AND ELIMINATION: A GUIDANCE MANUAL FOR PROGRAM DEVELOPMENT AND TECHNICAL ASSESSMENTS

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# Photo Acknowledgments

| *Figure Number* | *Source* |
|---|---|
| 3 | Regional Water Quality Control Board |
| 4 | Fort Worth Department of Environmental Management (DEM) |
| 5 | Fort Worth DEM |
| 7 | South Florida Water Management District (website) |
| 8 | Robert Pitt, University of Alabama |
| 14 | Robert Pitt |
| 28 (fire hydrant) | Fort Worth DEM |
| 34 (Chromium spill) | Fort Worth DEM |
| 34 (highly turbid discharge) | Rachel Calabro, Massachussets Department of Environmental Protection |
| 34 (industrial discharge) | Robert Pitt |
| 34 (paint) | Robert Pitt |
| 34 (Toronto industrial spill) | Robert Pitt |
| 34 (blood) | Fort Worth DEM |
| 34 (failing septic) | Snohomish County, WA |
| 34 (construction site) | Don Green, Franklin, TN |
| 34 (discharge of rinse water) | Rachel Calabro |
| 35 (natural foam) | Snohomish County, WA |
| 35 (high severity suds) | Fort Worth DEM |
| 35 (moderate severity oil) | R. Frymire |
| 35 (high severity oil) | Kelly Dinsmore, City of Newark, DE |
| 38 (bright red bacteria) | R. Frymire |
| 38 (Sporalitis filamentous) | Robert Ressl, City of Arlington, TX |
| 38 (extreme algal growth) | Mark Sommerfield, Montgomery Co., Maryland |
| 38 (brownish algae) | R. Frymire |
| 39 (*all* but 'brownish stain') | R. Frymire |
| 41 (*all*) | R. Frymire |
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# Foreword

A number of past projects have found that dry-weather flows discharging from storm drainage systems can contribute significant pollutant loadings to receiving waters. If these loadings are ignored (by only considering wet-weather stormwater runoff, for example), little improvement in receiving water conditions may occur. Illicit dry-weather flows originate from many sources. The most important sources typically include sanitary wastewater or industrial and commercial pollutant entries, failing septic tank systems, and vehicle maintenance activities.

Provisions of the Clean Water Act (1987) require National Pollutant Discharge Elimination System (NPDES) permits for storm water discharges. Section 402 (p)(3)(B)(ii) requires that permits for municipal separate storm sewers shall include a requirement to effectively prohibit problematic non-storm water discharges into storm sewers. Emphasis is placed on the elimination of inappropriate connections to urban storm drains. This requires affected agencies to identify and locate sources of non-storm water discharges into storm drains so they may institute appropriate actions for their elimination.

This Manual is intended to provide support and guidance, primarily to Phase II NPDES MS4 communities, for the establishment of Illicit Discharge Detection and Elimination (IDDE) programs and the design and procedures of local investigations of non-storm water entries into storm drainage systems. It also has application for Phase I communities looking to modify existing programs and community groups such as watershed organizations that are interested in providing reconnaissance and public awareness services to communities as part of watershed restoration activities.

This Manual was submitted in partial fulfillment of cooperative agreement X-82907801-0 under the sponsorship of the U.S. Environmental Protection Agency. This report covers a period from July 2001 to July 2004 and was prepared by the Center for Watershed Protection, Ellicott City, MD in cooperation with Robert Pitt of the University of Alabama.

Some references in the document pertain to work conducted during this project. This internal support information was developed as work tasks were completed and research findings were developed. In some cases, memoranda or technical support documents were prepared. Most of these documents are in "draft" form and have not been published. As a result, they should be considered supplemental and preliminary information that is not intended for widespread citation or distribution. In the References section, these documents are identified as "IDDE project support material" at the end of each citation. Interested readers can access these documents through the website link to the project archive and support information.

# Acknowledgments

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# Introduction

An up-to-date and comprehensive manual on techniques to detect and correct discharges in municipal storm drains has been unavailable until now. This has been a major obstacle for both Phase I and Phase II National Pollutant Discharge Elimination System (NPDES) municipal separate storm sewer system (MS4) communities that must have programs in place that detect, eliminate, and prevent illicit discharges to the storm drain system. Smaller Phase II communities, in particular, need simple but effective program guidance to comply with permits issued by the Environmental Protection Agency (EPA) and states. This manual provides communities with guidance on establishing and implementing an effective Illicit Discharge Detection and Elimination (IDDE) program.

Studies have shown that dry weather flows from the storm drain system may contribute a larger annual discharge mass for some pollutants than wet weather storm water flows (EPA, 1983 and Duke, 1997). Detecting and eliminating these illicit discharges involves complex detective work, which makes it hard to establish a rigid prescription to "hunt down" and correct all illicit connections. Frequently, there is no single approach to take, but rather a variety of ways to get from detection to elimination. Local knowledge and available resources can play significant roles in determining which path to take. At the very least, communities need to systematically understand and characterize their stream, conveyance, and storm sewer infrastructure systems. When illicit discharges are identified, they need to be removed. The process is ongoing and the effectiveness of a program should improve with time. In fact, well-coordinated IDDE programs can benefit from and contribute to other community-wide water resources-based programs, such as public education, storm water management, stream restoration, and pollution prevention.

This manual incorporates the experience of more than 20 Phase I communities that were surveyed about their practices, levels of program effort, and lessons learned (CWP, 2002). These communities took many different approaches to solve the IDDE problem, and provided great insights on common obstacles, setting realistic expectations and getting a hard job done right. Many of the IDDE methods presented in this manual were first developed and tested in many Phase I communities. Specific techniques applied in a community should be adapted to local conditions, such as dominant discharge types, land use, and generating sites.

Designed with a broad audience in mind, including agency heads, program managers, field technicians and water quality analysts, this manual is primarily focused on providing the thousands of Phase II communities that are now in the process of developing IDDE programs with guidance for the development and implementation of their own programs. The manual has been organized to address the broad range of administrative and technical considerations involved with setting up an effective IDDE program. The first 10 chapters of the Manual focus on "big picture" considerations needed to successfully get an IDDE program off the ground. The final four chapters provide detailed technical information on the methods to screen, characterize and remove illicit discharges in MS4 communities. These chapters present the state-of-the-practice on specific monitoring techniques and protocols.

In general, the content of this manual gets progressively more complex and technical toward the end. The basic organization of the manual is outlined below. The information is provided to help:

- Define important terminology and understand key illicit discharge concepts
- Conduct an audit to understand community needs and capabilities
- Establish adequate legal authority
- Develop a tracking system to map outfalls and document reported illicit discharges
- Conduct desktop analyses to prioritize targets for illicit discharge control
- Conduct rapid reconnaissance of the stream corridor to find problem outfalls
- Apply new analytical and field methods to find and fix illicit discharges
- Educate municipal employees and the public to prevent discharges
- Estimate costs to run a program and conduct specific investigations

**Chapter 1. The Basics of Illicit Discharges -** The many different sources and generating sites that can produce illicit discharges are described in Chapter 1. The chapter also outlines key concepts and terminology needed to understand illicit discharges, why they cause water quality problems and the regulatory context for managing them.

**Chapter 2. Components of an Effective Illicit Discharge Program** – This chapter presents an overall framework to build an IDDE program, by outlining eight key components of good programs. Each of the following eight chapters is dedicated to a key program component. The first page of the program component chapters is notated with a puzzle icon labeled with the applicable program component number.

**Chapter 3. Audit Existing Resources and Programs** – This chapter provides guidance on evaluating existing resources, regulations, and ongoing activities in your community to better address illicit discharges.

**Chapter 4. Establish Responsibility, Authority and Tracking** – This chapter presents guidance on how to identify the local agency who will be responsible for administering the IDDE program, and how to establish the legal authority to control illicit discharges by adapting an existing ordinance or adopting a new one. The chapter also describes how to set up a program tracking system needed to document discharges and local actions to respond to them.

**Chapter 5. Desktop Assessment of Illicit Discharge Potential** – The fifth chapter describes desktop analyses to process available mapping data to quickly characterize and screen illicit discharge problems at the community and subwatershed scale. Key factors include water quality, land use, development age, sewer infrastructure and outfall density. Rapid screening techniques are presented to define where to begin searching for illicit discharge problems in your community.

**Chapter 6. Developing Program Goals and Implementation Strategies** – Communities are required to establish and track measurable goals for their IDDE program under the NPDES MS4 permit program. This chapter recommends a series of potential program goals that can guide local efforts, as well as guidance on how to measure and track progress toward their achievement.

**Chapter 7. Searching for Illicit Discharge Problems in the Field** – This chapter briefly summarizes the major monitoring techniques to find illicit discharges, and discusses how to select the right combination of monitoring methods to incorporate into your local program.

**Chapter 8. Isolating and Fixing Individual Illicit Discharges** – The methods used to find and remove illicit discharges are briefly described in this chapter and include citizen hotlines and techniques to trace, locate and remove illicit discharge sources.

**Chapter 9. Preventing Illicit Discharges** – Prevention is a cost effective way to reduce pollution from illicit discharge. This chapter highlights a series of carrot and stick strategies to prevent illicit discharges.

**Chapter 10. IDDE Program Evaluation** – IDDE programs must continually evolve to changing local conditions. This chapter describes how to review and revisit program goals to determine if they are being met and to make any needed adjustments.

**Chapter 11. The Outfall Reconnaissance Inventory (ORI)** – The chapter presents detailed protocols to conduct rapid field screening of problem outfalls. The chapter also outlines the staff and equipment costs needed to conduct an ORI, and presents methods to organize, manage and interpret the data you collect.

**Chapter 12. Chemical Monitoring** – This chapter presents detailed guidance on the wide range of chemical monitoring options that can be used to identify the composition of illicit discharge flows. The chapter begins by describing different chemical indicators that have been used to identify illicit discharges, and presents guidance on how to collect samples for analysis. The chapter recommends a flow chart approach that utilizes four chemical indicators to distinguish the flow type. The chapter provides specific information on other analytical methods that can be used, as well as proper safety, handling, and disposal procedures. Simple and more sophisticated methods for interpreting monitoring data are discussed, along with comparative cost information.

**Chapter 13. Tracking Discharges to Their Source** – This chapter describes how to investigate storm drain systems to narrow and remove individual illicit discharges. These techniques include "trunk" investigations (e.g., video surveillance, damming, and infiltration and inflow studies) and on-site investigations (e.g., dye tests, smoke tests, and pollution prevention surveys). The pros and cons of each investigation technique are discussed, and comparative cost estimates are given.

**Chapter 14. Techniques to Fix Discharges** – This chapter provides tips on the best methods to repair or eliminate discharges. Specific advice is presented on how to identify responsible parties, develop pre-approved subcontractor lists, and estimate unit costs for typical repairs.

**Appendices** – Eleven technical appendices are provided at the end of the manual.

# Chapter 1: The Basics of Illicit Discharges

An understanding of the nature of illicit discharges in urban watersheds is essential to find, fix and prevent them. This chapter begins by defining the terms used to describe illicit discharges, and then reviews the water quality problems they cause. Next, the chapter presents the regulatory context for controlling illicit discharges, and reviews the experience local communities have gained in detecting and eliminating them.

## 1.1 Important Terminology and Key Concepts

This Manual uses several important terms throughout the text that merit upfront explanation. This section defines the terminology to help program managers perform important illicit discharge detective work in their communities. Key concepts are presented to classify illicit discharges, generating sites and control techniques.

### *Illicit Discharge*

The term "illicit discharge" has many meanings in regulation[1] and practice, but we use a four-part definition in this manual.

1. Illicit discharges are defined as a storm drain that has measurable flow during dry weather containing pollutants and/or pathogens. A storm drain with measurable flow but containing no pollutants is simply considered a discharge.

2. Each illicit discharge has a unique frequency, composition and mode of entry in the storm drain system.

3. Illicit discharges are frequently caused when the sewage disposal system interacts with the storm drain system. A variety of monitoring techniques is used to locate and eliminate illegal sewage connections. These techniques trace sewage flows from the stream or outfall, and go back up the pipes or conveyances to reach the problem connection.

4. Illicit discharges of other pollutants are produced from specific source areas and operations known as "generating sites." Knowledge about these generating sites can be helpful to locate and prevent non-sewage illicit discharges. Depending on the regulatory status of specific "generating sites," education, enforcement and other pollution prevention techniques can be used to manage this class of illicit discharges.

Communities need to define illicit discharges as part of an illicit discharge ordinance. Some non-storm water discharges to the MS4 may be allowable, such as discharges resulting from fire fighting activities and air conditioning condensate. Chapter 4 provides more detail on ordinance development.

[1] 40 CFR 122.26(b)(2) defines an illicit discharge as any discharge to an MS4 that is not composed entirely of storm water, except allowable discharges pursuant to an NPDES permit, including those resulting from fire fighting activities.

### Storm Drain

A **storm drain** can be either an *enclosed pipe* or an *open channel*. From a regulatory standpoint, **major** storm drains are defined as enclosed storm drain pipes with a diameter of 36 inches, or greater or open channels that drain more than 50 acres. For industrial land uses, major drains are defined as enclosed storm drain pipes 12 inches or greater in diameter and open channels that drain more than two acres. **Minor** storm drains are smaller than these thresholds. Both major and minor storm drains can be a source of illicit discharges, and both merit investigation.

Some "pipes" found in urban areas may look like storm drains but actually serve other purposes. Examples include foundation drains, weep holes, culverts, etc. These pipes are generally not considered storm drains from a regulatory or practical standpoint. Small diameter "straight pipes," however, are a common source of illicit discharges in many communities and should be investigated to determine if they are a pollutant source.

Not all dry weather storm drain flow contains pollutants or pathogens. Indeed, many communities find that storm drains with dry weather flow are, in fact, relatively clean. Flow in these drains may be derived from springs, groundwater seepage, or leaks from water distribution pipes. Consequently, field testing and/or water quality sampling are needed to confirm whether pollutants are actually present in dry weather flow, in order to classify them as an illicit discharge.

### Discharge Frequency

The **frequency** of dry weather discharges in storm drains is important, and can be classified as *continuous, intermittent or transitory.*

**Continuous** discharges occur most or all of the time, are usually easier to detect, and typically produce the greatest pollutant load. **Intermittent** discharges occur over a shorter period of time (e.g., a few hours per day or a few days per year). Because they are infrequent, intermittent discharges are hard to detect, but can still represent a serious water quality problem, depending on their flow type. **Transitory** discharges occur rarely, usually in response to a singular event such as an industrial spill, ruptured tank, sewer break, transport accident or illegal dumping episode. These discharges are extremely hard to detect with routine monitoring, but under the right conditions, can exert severe water quality problems on downstream receiving waters.

### Discharge Flow Types

Dry weather discharges are composed of one or more possible **flow types**:

- *Sewage and septage* flows are produced from sewer pipes and septic systems.
- *Washwater* flows are generated from a wide variety of activities and operations. Examples include discharges of gray water (laundry) from homes, commercial carwash wastewater, fleet washing, commercial laundry wastewater, and floor washing to shop drains.
- *Liquid wastes* refers to a wide variety of flows, such as oil, paint, and process water (radiator flushing water, plating bath wastewater, etc.) that enter the storm drain system.
- *Tap water* flows are derived from leaks and losses that occur during the distribution of drinking water in the water supply system. Tap water

discharges in the storm drain system may be more prevalent in communities with high loss rates (i.e., greater than 15%) in their potable water distribution system. (source of 15% is from National Drinking Water Clearinghouse http://www.nesc.wvu.edu/ndwc/articles/OT/FA02/Economics_Water.html)

- *Landscape irrigation* flows occur when excess potable water used for residential or commercial irrigation ends up in the storm drain system.
- *Groundwater and spring water* flows occur when the local water table rises above the bottom elevation of the storm drain (known as the invert) and enters the storm drain either through cracks and joints, or where open channels or pipes associated with the MS4 may intercept seeps and springs.

Water quality testing is used to conclusively identify flow types found in storm drains. Testing can distinguish illicit flow types (sewage/septage, washwater and liquid wastes) from cleaner discharges (tap water, landscape irrigation and ground water).

Each flow type has a distinct chemical fingerprint. Table 1 compares the pollutant fingerprint for different flow types in Alabama. The chemical fingerprint for each flow type can differ regionally, so it is a good idea to develop your own "fingerprint" library by sampling each local flow type.

In practice, many storm drain discharges represent a blend of several flow types, particularly at larger outfalls that drain larger catchments. For example, groundwater flows often dilute sewage thereby masking its presence. Chapter 12 presents several techniques to help isolate illicit discharges that are blended with cleaner discharges. Illicit discharges are also masked by high volumes of storm water runoff making it difficult and frequently impossible to detect them during wet weather periods.

### Mode of Entry

Illicit discharges can be further classified based on how they enter the storm drain system. The **mode of entry** can either be **direct** or **indirect. Direct entry** means that the discharge is directly connected to the storm drain pipe through a sewage pipe, shop drain, or other kind of pipe. Direct entry usually produces discharges that are continuous or intermittent. Direct entry usually occurs when two different kinds of "plumbing" are improperly connected. The three main situations where this occurs are:

Sewage cross-connections: A sewer pipe that is improperly connected to the storm drain system produces a continuous discharge of raw sewage to the pipe (Figure 1). Sewage cross-connections can occur in catchments where combined sewers or septic systems are converted to a separate sewer system, and a few pipes get "crossed."

Straight pipe: This term refers to relatively small diameter pipes that intentionally bypass the sanitary connection or septic drain fields, producing a direct discharge into open channels or streams as shown in Figure 2.

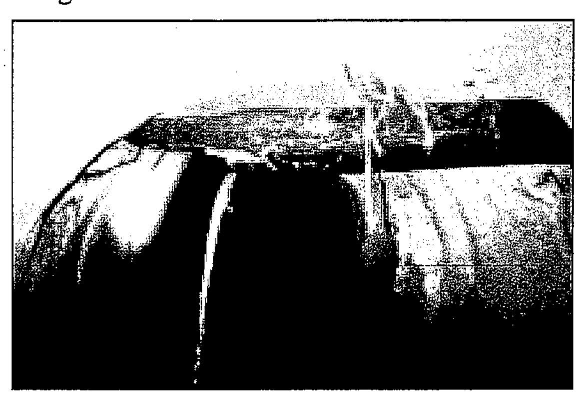

**Figure 1: Sewer Pipe Discharging to the Storm Drain System**

| Table 1: Comparative "Fingerprint" (Mean Values) of Flow Types | | | | | | |
|---|---|---|---|---|---|---|
| **Flow Type** | **Hardness (mg/L as CaCO3)** | **$NH_3$ (mg/L)** | **Potassium (mg/L)** | **Conductivity (μS/cm)** | **Fluoride (mg/L)** | **Detergents (mg/L)** |
| Sewage | 50 (0.26)* | 25 (0.53)* | 12 (0.21)* | 1215 (0.45)* | 0.7 (0.1)* | 9.7 (0.17)* |
| Septage** | 57(0.36) | 87 (0.4) | 19 (0.42) | 502 (0.42) | 0.93 (0.39) | 3.3 (1.33) |
| Laundry Washwater | 45 (0.33) | 3.2 (0.89) | 6.5 (0.78) | 463.5 (0.88) | 0.85 (0.4) | 758 (0.27) |
| Car Washwater | 71 (0.27) | 0.9 (1.4) | 3.6 (0.67) | 274 (0.45) | 1.2 (1.56) | 140 (0.2) |
| Plating Bath (Liquid Industrial Waste**) | 1430 (0.32) | 66 (0.66) | 1009 (1.24) | 10352 (0.45) | 5.1 (0.47) | 6.8 (0.68) |
| Radiator Flushing (Liquid Industrial Waste**) | 5.6 (1.88) | 26 (0.89) | 2801 (0.13) | 3280 (0.21) | 149 (0.16) | 15 (0.11) |
| Tap Water . | 52 (0.27) | <0.06 (0.55) | 1.3 (0.37) | 140 (0.07) | 0.94 (0.07) | 0 (NA) |
| Groundwater | 38 (0.19) | 0.06 (1.35) | 3.1 (0.55) | 149 (0.24) | 0.13 (0.93) | 0 (NA) |
| Landscape Irrigation | 53 (0.13) | 1.3 (1.12) | 5.6 (0.5) | 180 (0.1) | 0.61 (0.35) | 0 (NA) |

** The number in parentheses after each concentration is the Coefficient of Variation; NA = Not Applicable*
*** All values are from Tuscaloosa, AL monitoring except liquid wastes and septage, which are from Birmingham, AL.*
*Sources: Pitt (project support material) and Pitt et al. (1993)*

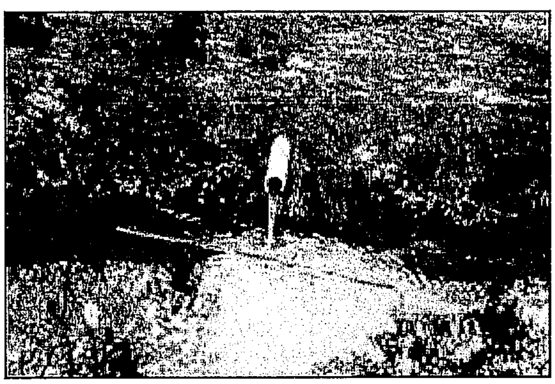

**Figure 2: Direct Discharge from a Straight Pipe**

> **Sewage** has the greatest potential to produce *direct* illicit discharges within any urban subwatershed, regardless of the diverse land uses that it comprises. The most commonly reported sewage-related direct discharges are broken sanitary sewer lines (81% of survey respondents), cross-connections (71% of survey respondents), and straight pipe discharges (38% of survey respondents). (CWP, 2002).

Industrial and commercial cross-connections: These occur when a drain pipe is improperly connected to the storm drain system producing a discharge of wash water, process water or other inappropriate flows into the storm drain pipe. A floor shop drain that is illicitly connected to the storm drain system is illustrated in Figure 3. Older industrial areas tend to have a higher potential for illicit cross-connections.

**Indirect** entry means that flows generated outside the storm drain system enter through storm drain inlets or by infiltrating through the joints of the pipe. Generally, indirect modes of entry produce intermittent or transitory discharges, with the exception of groundwater seepage. The five main modes of indirect entry for discharges include:

Groundwater seepage into the storm drain pipe: Seepage frequently occurs in storm drains after long periods of above average rainfall. Seepage discharges can be either continuous or intermittent, depending on the depth of the water table and the season. Groundwater seepage usually consists of relatively clean water that is not an illicit discharge by itself, but can mask other illicit discharges. If storm drains are located close to sanitary sewers, groundwater seepage may intermingle with diluted sewage.

Spills that enter the storm drain system at an inlet: These transitory discharges occur when a spill travels across an impervious surface and enters a storm drain inlet. Spills can occur at many industrial, commercial and transport-related sites. A very common example is an oil or gas spill from an accident that then travels across the road and into the storm drain system (Figure 4).

Dumping a liquid into a storm drain inlet: This type of transitory discharge is created when liquid wastes such as oil, grease, paint, solvents, and various automotive fluids are dumped into the storm drain (Figure 5). Liquid dumping occurs intermittently at sites that improperly dispose of rinse water and wash water during maintenance and cleanup operations. A common example is cleaning deep fryers in the parking lot of fast food operations.

Outdoor washing activities that create flow to a storm drain inlet: Outdoor washing may or may not be an illicit discharge, depending on the nature of the generating site that produces the wash water. For example, hosing off individual sidewalks and driveways may not generate significant flows or pollutant loads. On the other hand, routine washing of fueling areas, outdoor storage areas, and parking lots (power washing), and construction equipment cleanouts may result in unacceptable pollutant loads (Figure 6).

Non-target irrigation from landscaping or lawns that reaches the storm drain system: Irrigation can produce intermittent discharges from over-watering or misdirected sprinklers that send tap water over impervious areas (Figure 7). In some instances, non-target irrigation can produce unacceptable loads of nutrients, organic matter or pesticides. The most common example is a discharge from commercial landscaping areas adjacent to parking lots connected to the storm drain system.

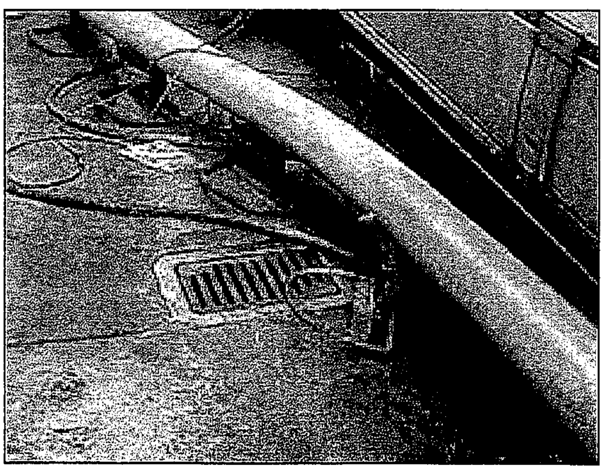

**Figure 3: A common industrial cross connection is a floor drain that is illicitly connected to a storm drain**

**Figure 4: Accident spills are significant sources of illicit discharges to the storm drain system**



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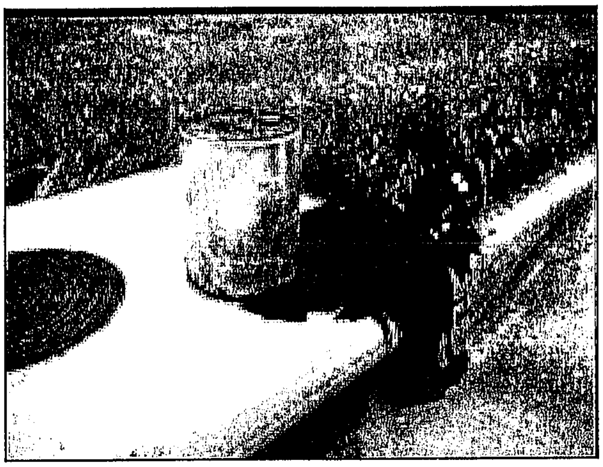


Figure 5: Dumping at a storm drain inlet


Figure 6: Routine outdoor washing and rinsing can cause illicit discharges


Figure 7: Non-target landscaping irrigation water

### *Land Use and Potential Generating Sites*

**Land use** can predict the potential for indirect discharges, which are often intermittent or transitory. Many indirect discharges can be identified and prevented using the concept of "generating sites," which are sites where common operations can generate indirect discharges in a community. Both research and program experience indicate that a small subset of generating sites within a broader land use category can produce most of the indirect discharges. Consequently, the density of potential generating sites within a subwatershed may be a good indicator of the severity of local illicit discharge problems. Some common generating sites within major land use categories are listed in Table 2, and described below.

Residential Generating Sites: Failing septic systems were the most common residential discharge reported in 33% of IDDE programs surveyed (CWP, 2002). In addition, indirect residential discharges were also frequently detected in 20% of the IDDE programs surveyed, which consisted of oil dumping, irrigation overflows, swimming pool discharges, and car washing. Many indirect discharges are caused by common residential behaviors and may not be classified as "illicit" even though they can contribute to water quality problems. With the exception of failing septic systems and oil dumping, most communities have chosen education rather than enforcement as the primary tool to prevent illicit discharges from residential areas.

Commercial Generating Sites: Illicit discharges from commercial sites were reported as frequent in almost 20% of local IDDE programs surveyed (CWP, 2002). Typical commercial discharge generators included operations such as outdoor washing; disposal of food wastes; car fueling, repair, and washing; parking lot power washing; and poor dumpster management. Recreational areas, such as marinas and campgrounds, were also reported to be a notable source of sewage discharges. It is important to note that not all businesses within a generating category actually produce illicit discharges; generally only a relatively small fraction do. Consequently, on-site inspections of individual businesses are needed to confirm whether a property is actually a generating site.

**Sewage** can also be linked to significant *indirect* illicit discharges in the form of sanitary sewer overflows (52% of survey respondents), sewage infiltration/inflow (48% of survey respondents), and sewage dumping from recreational vehicles (33% of survey respondents) (CWP, 2002).

| Table 2: Land Uses, Generating Sites and Activities That Produce Indirect Discharges | | |
|---|---|---|
| **Land Use** | **Generating Site** | **Activity that Produces Discharge** |
| Residential | • Apartments<br>• Multi-family<br>• Single Family Detached | • Car Washing<br>• Driveway Cleaning<br>• Dumping/Spills (e.g., leaf litter and RV/boat holding tank effluent)<br>• Equipment Washdowns<br>• Lawn/Landscape Watering<br>• Septic System Maintenance<br>• Swimming Pool Discharges |
| Commercial | • Campgrounds/RV parks<br>• Car Dealers/Rental Car Companies<br>• Car Washes<br>• Commercial Laundry/Dry Cleaning<br>• Gas Stations/Auto Repair Shops<br>• Marinas<br>• Nurseries and Garden Centers<br>• Oil Change Shops<br>• Restaurants<br>• Swimming Pools | • Building Maintenance (power washing)<br>• Dumping/Spills<br>• Landscaping/Grounds Care (irrigation)<br>• Outdoor Fluid Storage<br>• Parking Lot Maintenance (power washing)<br>• Vehicle Fueling<br>• Vehicle Maintenance/Repair<br>• Vehicle Washing<br>• Washdown of greasy equipment and grease traps |
| Industrial | • Auto recyclers<br>• Beverages and brewing<br>• Construction vehicle washouts<br>• Distribution centers<br>• Food processing<br>• Garbage truck washouts<br>• Marinas, boat building and repair<br>• Metal plating operations<br>• Paper and wood products<br>• Petroleum storage and refining<br>• Printing | • All commercial activities<br>• Industrial process water or rinse water<br>• Loading and un-loading area washdowns<br>• Outdoor material storage (fluids) |
| Institutional | • Cemeteries<br>• Churches<br>• Corporate Campuses<br>• Hospitals<br>• Schools and Universities | • Building Maintenance (e.g., power washing)<br>• Dumping/Spills<br>• Landscaping/Grounds Care (irrigation)<br>• Parking Lot Maintenance (power washing)<br>• Vehicle Washing |
| Municipal | • Airports<br>• Landfills<br>• Maintenance Depots<br>• Municipal Fleet Storage Areas<br>• Ports<br>• Public Works Yards<br>• Streets and Highways | • Building Maintenance (power washing)<br>• Dumping/Spills<br>• Landscaping/Grounds Care (irrigation)<br>• Outdoor Fluid Storage<br>• Parking Lot Maintenance (power washing)<br>• Road Maintenance<br>• Spill Prevention/Response<br>• Vehicle Fueling<br>• Vehicle Maintenance/Repair<br>• Vehicle Washing |

Industrial Generating Sites: Industrial sites produce a wide range of flows that can cause illicit discharges. The most common continuous discharges are operations involving the disposal of rinse water, process water, wash water and contaminated, non-contact cooling water. Spills and leaks, ruptured pipes, and leaking underground storage tanks are also a source of indirect discharges. Illicit discharges from industry were detected in nearly 25% of the local IDDE programs surveyed (CWP, 2002).

Industries are classified according to hundreds of different Standard Industrial Classification (SIC) codes. The SIC coding system also includes commercial, institutional and municipal operations[2]. Many industries are required to have storm water pollution prevention and spill response plans under EPA's Industrial Storm Water NPDES Permit Program. A complete list of the industries covered by the Storm Water NPDES Permit Program can be found in Appendix A. The appendix also rates each industrial category based on its potential to produce illicit discharges, based on analysis by Pitt (2001).

Institutional Generating Sites: Institutions such as hospitals, corporate campuses, colleges, churches, and cemeteries can be generating sites if routine maintenance practices/operations create discharges from parking lots and other areas. Many large institutional sites have their own areas for fleet maintenance, fueling, outdoor storage, and loading/unloading that can produce indirect discharges.

Municipal Generating Sites: Municipal generating sites include operations that handle solid waste, water, wastewater, street and storm drain maintenance, fleet washing, and yard waste disposal. Transport-related areas such as streets and highways, airports, rail yards, and ports can also generate indirect discharges from spills, accidents and dumping.

## *Finding, Fixing, and Preventing Illicit Discharges*

The purpose of an IDDE program is to find, fix and prevent illicit discharges, and a series of techniques exist to meet these objectives. The remainder of the manual describes the major tools used to build a local IDDE program, but they are briefly introduced below:

### Finding Illicit Discharges

The highest priority in most programs is to find any continuous and intermittent sewage discharges to the storm drain system. A range of monitoring techniques can be used to find sewage discharges. In general, monitoring techniques are used to find problem areas and then trace the problem back up the stream or pipe to identify the ultimate generating site or connection. Monitoring can sometimes pick up other types of illicit discharge that occur on a continuous or intermittent basis (e.g., wash water and liquid wastes). Monitoring techniques are classified into three major groups:

- Outfall Reconnaissance Inventory
- Indicator Monitoring at Storm Water Outfalls and In-stream
- Tracking Discharges to their Source

[2] More recently, federal agencies including EPA, have adopted the North American Industry Classification System (NAICS, pronounced "Nakes") as the industry classification system. For more information on the NAICS and how it correlates with SIC, visit http://www.census.gov/epcd/www/naics.html.

**!!! Caution !!!**

Using land use as an indicator for certain flow types such as sewage is often less reliable than other factors in predicting the potential severity of sewage discharges. More useful assessment factors for illicit sewage discharges include the age of the sewer system, which helps define the physical integrity and capacity of the pipe network, as well as age of development, which reveals the plumbing codes and practices that existed when individual connections were made over time. Two particular critical phases in the sewer history of a subwatershed are when sanitary sewers were extended to replace existing septic systems, or when a combined sewer was separated. The large number of new connections and/or disconnections during these phases increases the probability of bad plumbing.

## Fixing Illicit Discharges

Once sewage discharges or other connections are discovered, they can be fixed, repaired or eliminated through several different mechanisms. Communities should establish targeted education programs along with legal authority to promote timely corrections. A combination of carrots and sticks should be available to deal with the diversity of potential dischargers.

## Preventing Illicit Discharges

The old adage "an ounce of prevention is worth a pound of cure" certainly applies to illicit discharges. Transitory discharges from generating sites can be minimized through pollution prevention practices and well-executed spill management and response plans. These plans should be frequently practiced by local emergency response agencies and/or trained workers at generating sites. Other pollution prevention practices are described in Chapter 9 and explored in greater detail in Manual 8 of the Urban Subwatershed Restoration Manual Series (Schueler *et al.*, 2004).

**National Urban Runoff Project**

EPA's National Urban Runoff Project (NURP) studies highlighted the significance of pollutants from illicit entries into urban storm sewerage (EPA, 1983). Such entries may be evidenced by flow from storm sewer outfalls following substantial dry periods. Such flow, frequently referred to as "baseflow" or "dry weather flow", could be the result of direct "illicit connections" as mentioned in the NURP final report (EPA, 1983), or could result from indirect connections (such as leaky sanitary sewer contributions through infiltration). Many of these dry weather flows are continuous and would therefore occur during rain induced runoff periods. Pollutant contributions from dry weather flows in some storm drains have been shown to be high enough to significantly degrade water quality because of their substantial contributions to the annual mass pollutant loadings to receiving waters (project research).

## 1.2 The Importance of Illicit Discharges in Urban Water Quality

Dry and wet weather flows have been monitored during several urban runoff studies. These studies have found that discharges observed at outfalls during dry weather were significantly different from wet weather discharges. Data collected during the 1984 Toronto Area Watershed Management Strategy Study monitored and characterized both storm water flows and baseflows (Pitt and McLean, 1986). This project involved intensive monitoring in two test areas (a mixed residential/commercial area and an industrial area) during warm, cold, wet, and dry weather. The annual mass discharges of many pollutants were found to be greater in dry weather flows than in wet weather flows.

A California urban discharge study identified commercial and residential discharges of oil and other automobile-related fluids as a common problem based on visual observations (Montoya, 1987). In another study, visual inspection of storm water pipes discharging to the Rideau River in Ontario found leakage from sanitary sewer joints or broken pipes to be a major source of storm drain contamination (Pitt, 1983).

Several urban communities conducted studies to identify and correct illicit connections to their storm drain systems during the mid-1980s. These studies were usually taken in response to receiving water quality problems or as part of individual NURP research projects. The studies indicated the magnitude and extent of cross-connection problems in many urban watersheds. For example, Washtenaw County, Michigan tested businesses to locate direct illicit connections to the county storm drain system. Of the 160 businesses tested, 38% were found to have illicit storm drain connections (Schmidt and Spencer, 1986). An investigation of the separate storm sewer system in Toronto, Ontario revealed 59% of outfalls had dry weather flows, while 14% of the total outfalls were characterized as "grossly polluted," based on a battery of chemical tests (GLA, 1983). An inspection of the 90 urban storm water outfalls draining into Grays Harbor in Washington showed that 32% had dry weather flows (Pelletier and Determan, 1988). An additional 19 outfalls were considered suspect, based on visual observation and/or elevated pollutant levels compared to typical urban storm water runoff.

The Huron River Pollution Abatement Program ranks as one of the most thorough and systematic early investigations of illicit discharges (Washtenaw County, 1988). More than a thousand businesses, homes and other buildings located in the watershed were dye tested. Illicit connections were found at 60% of the automobile-related businesses tested, which included service stations, automobile dealerships, car washes, and auto body and repair shops. All plating shops inspected were found to have illicit storm drain connections. Additionally, 67% of the manufacturers, 20% of the private service agencies and 88% of the wholesale/retail establishments tested were found to have illicit storm sewer connections. Of the 319 homes dye tested, 19 were found to have direct sanitary connections to storm drains. The direct discharge of rug-cleaning wastes into storm drains by carpet cleaners was also noted as a common problem.

Eliminating illicit discharges is a critical component to restoring urban watersheds. When bodies of water cannot meet designated uses for drinking water, fishing, or recreation, tourism and waterfront home values may fall; fishing and shellfish harvesting can be restricted or halted; and illicit discharges can close beaches, primarily as a result of bacteria contamination. In addition to the public health and economic impacts associated with illicit discharges, significant impacts to aquatic life and wildlife are realized. Numerous fish kills and other aquatic life losses have occurred in watersheds as a result of illicit or accidental dumping and spills that have resulted in lethal pollutant concentrations in receiving waters.

## 1.3 Regulatory Background For Illicit Discharges

The history of illicit discharge regulations is long and convoluted, reflecting an ongoing debate as to whether they should be classified as a point or nonpoint source of pollution. The Clean Water Act amendments of 1987 contained the first provisions to specifically regulate discharges from storm drainage systems. Section 402(p)(3)(B) provides that "permits for such discharges:

(i) May be issued on a system or jurisdiction-wide basis

(ii) Shall include a requirement to effectively prohibit non-storm water discharges into the storm sewers; and

(iii) Shall require controls to reduce the discharge of pollutants to the maximum extent practical including management practices, control techniques and system design and engineering methods, and such provisions as the Administrator or the State determines appropriate for the control of such pollutants."

In the last 15 years, NPDES permits have gradually been applied to a greater range of communities. In 1990, EPA issued a final rule, known as Phase I to implement section 402(p) of the Clean Water Act through the NPDES permit system. The EPA effort expanded in December 1999, when the Phase II final rule was issued. A summary of how both rules pertain to MS4s and illicit discharge control is provided below.

### *Summary of NPDES Phase I Requirements*

The NPDES Phase I permit program regulates municipal separate storm sewer systems (MS4s) meeting the following criteria:

- Storm sewer systems located in an incorporated area with a population of 100,000 or more
- Storm sewer systems located in 47 counties identified by EPA as having populations over 100,000 that were unincorporated but considered urbanized areas
- Other storm sewer systems that are specially designated based on the location of storm water discharges with respect to waters of the United States, the size of the discharge, the quantity and nature of the pollutants discharged, and the interrelationship to other regulated storm sewer systems, among other factors

An MS4 is defined as any conveyance or system of conveyances that is owned or operated by a state or local government entity designed for collecting and conveying storm water, which is not part of a Publicly Owned Treatment Works. The total number of permitted MS4s in the Phase I program is 1,059.

**PHASE I HIGHLIGHTS**

| | |
|---|---|
| **Who must meet the requirements?** | MS4s with population ≥100,000 |
| **How many Phase I communities exist nationally?** | 1,059 |
| **What are the requirements related to illicit discharges?** | Develop programs to prevent, detect and remove illicit discharges |

Phase I MS4s were required to submit a two-part application. The first part required information regarding existing programs and the capacity of the municipality to control pollutants. Part 1 also required identification of known "major" outfalls[3] discharging to waters of the United States, and a field screening analysis of representative major outfalls to detect illicit connections. Part 2 of the application required identification of additional major outfalls, limited monitoring, and a proposed storm water management plan (EPA, 1996).

Phase I communities were required to develop programs to detect and remove illicit discharges, and to control and prevent improper disposal into the MS4 of materials such as used oil or seepage from municipal sanitary sewers. The illicit discharge programs were required to include the following elements:

- Implementation and enforcement of an ordinance, orders or similar means to prevent illicit discharges to the MS4
- Procedures to conduct ongoing field screening activities during the life of the permit
- Procedures to be followed to investigate portions of the separate storm sewer system that, based on the results of the field screening required in Part 2 of the application, indicate a reasonable potential for containing illicit discharges or other sources of non-storm water
- Procedures to prevent, contain, and respond to spills that may discharge into the MS4
- A program to promote, publicize, and facilitate public reporting of the presence of illicit discharges or water quality impacts associated with discharges from the MS4
- Educational activities, public information activities, and other appropriate activities to facilitate the proper management and disposal of used oil and toxic materials
- Controls to limit infiltration of seepage from municipal sanitary sewers to the MS4

[3] A "major" outfall is defined as an MS4 outfall that discharges from a single pipe with an inside diameter of at least 36 inches, or discharges from a single conveyance other than a circular pipe serving a drainage area of more than 50 acres. An MS4 outfall with a contributing industrial land use that discharges from a single pipe with an inside diameter of 12 inches or more or discharges from a single conveyance other than a circular pipe serving a drainage area of more than two acres.

### *Summary of NPDES Phase II Requirements*

The Phase II Final Rule, published in the Federal Register regulates MS4s that meet both of the following criteria:

- Storm sewer systems that are not a medium or large MS4 covered by Phase I of the NPDES Program
- Storm sewer systems that are located in an Urbanized Area (UA) as defined by the Bureau of the Census, <u>or</u> storm sewer systems located outside of a UA that are designated by NPDES permitting authorities because of one of the following reasons:
  - The MS4's discharges cause, or have the potential to cause, an adverse impact on water quality
  - The MS4 contributes substantially to the pollutant loadings of a physically interconnected MS4 regulated by the NPDES storm water program

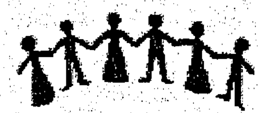
MS4s that meet the above criteria are referred to as regulated small MS4s. Each regulated small MS4 must satisfy six minimum control measures:

1. Public education and outreach
2. Public participation/involvement
3. Illicit discharge detection and elimination
4. Construction site runoff control
5. Post-construction runoff control
6. Pollution prevention/Good housekeeping

Under the third minimum measure, an illicit discharge is defined as any discharge to an MS4 that is not composed entirely of storm water, except allowable discharges pursuant to an NPDES permit, including those resulting from fire fighting activities (40 CFR 122.26(b)(2)). To satisfy this minimum measure, the regulated small MS4 must include the following five components:

- Develop a storm sewer system map that shows the location of all outfalls and the names and locations of all waters of the United States that receive discharges from those outfalls
- Prohibit, through ordinance or other regulatory mechanism, non-storm water discharges into the storm sewer system and implement appropriate enforcement procedures and actions
- Develop and implement a plan to detect and address illicit discharges to the MS4
- Educate public employees, businesses, and the general public of hazards associated with illicit discharges and improper disposal of waste
- Identify the appropriate best management practices and measurable goals for this minimum measure

### PHASE II HIGHLIGHTS

| | |
|---|---|
| **Who must meet the requirements?** | Selected small MS4s  |
| **How many Phase I communities exist nationally?** | EPA estimates are 5,000-6,000 |
| **What are the requirements related to illicit discharges?** | Develop programs to prevent, detect and remove illicit discharges |
| **What is the deadline for meeting these requirements?** | Permits issued by March 10, 2003. Programs must be fully implemented by the end of first permit term (5 years) |

In the regulation, EPA recommends that the plan to detect and address illicit discharges include procedures for:

- Locating priority areas likely to have illicit discharges (which may include visually screening outfalls during dry weather and conducting field tests of selected pollutants)
- Tracing the source of an illicit discharge
- Removing the source of the discharge
- Program evaluation and assessment

## 1.4 Experience Gained in Phase I

The Center for Watershed Protection conducted a series of surveys and interviews with Phase I communities to determine the current state of the practices utilized in local IDDE programs, and to identify the most practical, low-cost, and effective techniques to find, fix and prevent discharges. The detailed survey included 24 communities from various geographic and climatic regions in the United States. Some of the key findings of the survey are presented below (CWP, 2002)[4].

- Lack of staff significantly hindered implementation of a successful IDDE program. Phase I communities rely heavily on the expertise of their field staff – practical expertise that has been acquired over many years as programs gradually developed. Methods or approaches recommended for Phase II communities should be less dependent on professional judgment.

[4] Survey results are based on responses from 24 jurisdictions from 16 states. Surveys were supplemented by on-site interviews of staff of eight IDDE programs: Baltimore City, MD; Baltimore County, MD; Boston Water and Sewer Commission (BWSC), MA; Cambridge, MA; Dayton, OH; Raleigh, NC; Wayne County, MI; and Fort Worth, TX. Jurisdictions selected for the survey and interviews represent a variety of geographic and climatic regions. The EPA storm water coordinators for each region of the country were contacted for recommendations on jurisdictions to include in the survey. Also, a variety of jurisdiction sizes in terms of population, IDDE program service area, and land use was targeted.

- Clear and effective ordinance language should be adopted by Phase II communities to ensure that all potential sources of illicit discharges are prohibited, and that the community has sufficient legal authority to inspect private properties and enforce corrections.

- Many communities lacked up-to-date mapping resources, and found that mapping layers such as storm sewers, open drainage channels, waters of the U.S., outfalls, and land use were particularly useful to conduct and prioritize effective field investigations.

- Outfall screening required the greatest staff and equipment resources, and did not always find problem outfalls. Communities recommended a fast and efficient sampling approach that utilizes a limited number of indicator parameters at each outfall to find problem outfalls.

- When purchasing equipment, Phase II programs should communicate with other jurisdictions to consider sharing field equipment and laboratory costs.

- Use of some discharge tracers has proven challenging and sometimes fruitless, because of false or ambiguous results and complex or hazardous analytical methods. Accurate, cost-effective, and safe monitoring methods are needed to effectively use tracers.

- Municipal IDDE programs worked best when they integrated illicit discharge control in the wider context of urban watershed restoration. Table 3 provides some examples of how greater interagency cooperation can be achieved by linking restoration program areas.

In summary, survey communities expressed a strong need for relatively simple guidance to perform illicit discharge investigations. To address this need, the Manual has been designed to make simple program and technical recommendations for Phase II communities to develop cost-effective IDDE programs.

| Table 3: Linking Other Municipal Programs to IDDE Program Needs | |
|---|---|
| **Watershed-Related Program** | **How Program Relates to IDDE Program Needs** |
| Subwatershed Mapping and Analysis | • Mapping and aerial photography are critical tools needed for illicit connection detection surveys. GIS tax map layers are often useful to identify property ownership. |
| Rapid Assessment of Stream Corridors | • Observations from physical stream assessments are often useful in identifying problem areas, including dry weather flow outfalls, illegal dumping, and failing infrastructure locations. |
| Watershed Monitoring and Reporting | • Compiled water quality and other indicator data can be useful in targeting problem areas. |
| Stream Restoration Opportunities | • Stream restoration opportunities can often be coordinated with sewer infrastructure upgrades and maintenance. |
| Watershed Education | • Educating the public about unwanted discharges can save programs money by generating volunteer networks to report and locate problem areas. Better awareness by the public can also reduce the likelihood of unintentional cross-connections. |
| Pollution Prevention for Generating Sites | • Providing incentives to businesses to inspect and correct connections can save programs money. |

# Chapter 2: Components of an Effective IDDE Program

The prospect of developing and administering an IDDE program can be daunting, complex and challenging in many communities. This Chapter organizes and simplifies the basic tasks needed to build a program. In general, a community should consider eight basic program components, as follows:

**1. Audit Existing Resources and Programs** – The first program component reviews existing local resources, regulations, and responsibilities that bear on illicit discharge control in the community. A systematic audit defines local needs and capabilities, and provides the foundation for developing the initial IDDE program plan over the first permit cycle.

**2. Establish Responsibility, Authority and Tracking** – This component finds the right "home" for the IDDE program within existing local departments and agencies. It also establishes the local legal authority to regulate illicit discharges, either by amending an existing ordinance, or crafting a new illicit discharge ordinance. This program component also involves creation of a tracking system to report illicit discharges, suspect outfalls, and citizen complaints, and to document local management response and enforcement efforts.

**3. Complete a Desktop Assessment of Illicit Discharge Potential** – Illicit discharges are not uniformly distributed across a community, but tend to be clustered within certain land uses, subwatersheds, and sewage infrastructure eras. This program component helps narrow your search for the most severe illicit discharge problems, through rapid analysis of existing mapping and water quality monitoring data.

**4. Develop Program Goals and Implementation Strategies** – This program component integrates information developed from the first three program components to establish measurable goals for the overall IDDE program during the first permit cycle. Based on these goals, managers develop specific implementation strategies to improve water quality and measure program success.

**5. Search for Illicit Discharge Problems in the Field** – This component involves rapid outfall screening to find problem outfalls within priority subwatersheds. Results of outfall surveys are then used to design a more sophisticated outfall monitoring system to identify flow types and trace discharge sources. Many different monitoring options exist, depending on local needs and discharge conditions.

**6. Isolate and Fix Individual Discharges** – Once illicit discharge problems are found, the next step is to trace them back up the pipe to isolate the specific source or improper connection that generates them. Thus, this program component improves local capacity to locate specific discharges, make needed corrections, and take any enforcement actions.

**7. Prevent Illicit Discharges** – Many transitory and intermittent discharges are produced by careless practices at the home or workplace. This important program component uses a combination of education and enforcement to promote better pollution prevention practices. A series of carrots and sticks is used to reach out to targeted individuals to prevent illegal or unintentional illicit discharges.

**8. Evaluate the Program** – The last component addresses the ongoing management of the IDDE program. The measurable goals set for the IDDE program are periodically reviewed and revisited to determine if progress is being made, or implementation strategies need to be adjusted.

Within each program component, a community has many options to choose, based on its size, capability and the severity of its illicit discharge problems. Chapters 3 through 10 address each IDDE program component in more detail, and summarize its purpose, methods, desired product or outcome, and budget implications. The remainder of each chapter provides program managers with detailed guidance to choose the best options to implement the program component in their community.

Scheduling of the eight IDDE program components is not always sequential and may overlap in some cases. In general, the first four program components should be scheduled for completion within the first year of the permit cycle in order to develop an effective program for the remaining years of the permit. Table 4 summarizes the specific tasks and products associated with each IDDE program component. The scheduling, costs and expertise needed for each IDDE program component are compared in Table 5.

**Table 4: Key Tasks and Products in IDDE Program Implementation**

| Program Component | Key Tasks | Products |
|---|---|---|
| 1. Audit existing programs | • Infrastructure Profile<br>• Existing Legal Authority<br>• Available Mapping<br>• Experienced Field Crews<br>• Access to Lab Services<br>• Education and Outreach Outlets<br>• Discharge Removal Capability<br>• Program Budget and Financing | • Agreement on Lead Agency<br>• 5 year Program Development Plan<br>• First Year Budget and Scope of Work |
| 2. Establish responsibility and authority | • Review Existing Ordinances<br>• Define "Illicit"<br>• Provisions for Access/Inspections<br>• Select Enforcement Tools<br>• Design Tracking System | • Adopt or Amend Ordinance<br>• Implement Tracking System |
| 3. Desktop assessment of illicit discharge potential | • Delineate Subwatersheds<br>• Compile Mapping Layers/Data<br>• Define Discharge Screening Factors<br>• Screen Subwatersheds for Illicit Discharge Potential<br>• Generate Maps for Field Screening | • Prioritize Subwatersheds for Field Screening |
| 4. Develop program goals and strategies | • Community Analysis of Illicit Discharge<br>• Public Involvement | • Measurable Program Goals<br>• Implementation Strategies |

**Table 4: Key Tasks and Products in IDDE Program Implementation**

| Program Component | Key Tasks | Products |
|---|---|---|
| 5. Search for illicit discharges problems in the field | • Outfall Reconnaissance Inventory (ORI)<br>• Integrate ORI data in Tracking System<br>• Follow-up Monitoring at Suspect Outfalls | • Initial Storm Drain Outfall Map<br>• Develop Monitoring Strategy |
| 6. Isolate and fix individual discharges | • Implement Pollution Hotline<br>• Trunk and On-site Investigations<br>• Corrections and Enforcement | • Maintain Tracking System |
| 7. Prevent illicit discharges | • Select Key Discharge Behaviors<br>• Prioritize Outreach Targets<br>• Choose Effective Carrots and Sticks<br>• Develop Budget and Delivery System | • Implement Residential, Commercial, Industrial or Municipal Pollution Prevention Programs |
| 8. Program evaluation | • Analyze Tracking System<br>• Characterize Illicit Discharges Detected<br>• Update Goals and Strategies | • Annual Reports<br>• Permit Renegotiation |

**Table 5: Comparison of IDDE Program Components**

| IDDE Program Component | When To Do It | Startup Costs | Annual Cost | Expertise Level | Type of Expertise |
|---|---|---|---|---|---|
| 1. Audit | Immediately | $ | -0- | ?? | Planning/Permitting |
| 2. Authority | Year 1 | $$ | $ | ?? | Legal |
| 3. Desktop Analysis | Year 1 | $$ | -0- | ??? | GIS |
| 4. Goals/Strategies | Year 1 | $ | -0- | ?? | Stakeholder Management |
| 5 Field Search/Monitoring | Year 2 to 5 | $$ | $$$$ | ??? | Monitoring |
| 6 Isolate and Fix | Year 2 to 5 | $ | $$ | ??? | Pipe and Site Investigations |
| 7. Prevention | Year 2 to 5 | $$ | $$$ | ?? | Education |
| 8. Evaluation/Tracking | Annually | -0- | $ | ? | Data Analysis |
| Key: $ = <$10,000<br>$$ = $10,000 - 25,000<br>$$$ = $25,000 - 50,000<br>$$$$ = > $50,000 | ? - Simple<br>?? - Moderately Difficult<br>??? - Complex | | | | |

## 2.1 Management Tips To Develop an Effective IDDE Program

Every community will develop a unique IDDE program that reflects its size, development history, land use, and infrastructure. Still, some common threads run through effective and well-managed local IDDE programs. Below are some tips on building an effective local.

*1. Go after continuous sewage discharges first.* Effective programs place a premium on keeping sewage out of the storm drain system. Continuous sewage discharges pose the greatest threat to water quality and public health, produce large pollutant loads, and can generally be permanently corrected when the offending connection is finally found. Intermittent or indirect discharges are harder to detect, and more difficult to fix.

*2. Put together an interdisciplinary and interagency IDDE development team.* A broad range of local expertise needs to be coordinated to develop the initial IDDE plan, as indicated in Table 5. Effective programs assemble an interagency program development team that possesses the diverse skills and knowledge needed for the program, ranging from legal analysis, GIS, monitoring, stakeholder management and pipe repairs.

*3. Educate everybody about illicit discharges.* Illicit discharge control is a new and somewhat confusing program to the public, elected officials, and many local agencies. Effective programs devote considerable resources to educate all three groups about the water quality impacts of illicit discharges.

*4. Understand your infrastructure.* Finding illicit discharges is like finding a needle in a haystack on a shoestring budget. Many indirect or transitory discharges are extremely difficult to catch through outfall screening. Therefore, effective programs seek to understand the history and condition of their storm water and sewer infrastructure to find the combinations that create the greatest risk for illicit discharge. Effective programs also screen land uses to locate generating sites within targeted subwatersheds. For example, knowing the proximity of the infrastructure to the groundwater table or knowing that the sewer collection system has a long transit time can influence the indicator parameters and associated thresholds that a community chooses to target.

*5. Walk all of your streams in the first permit cycle.* Perform a rapid Outfall Reconnaissance Inventory (ORI) on every mile of stream or channel in the community, starting with the subwatersheds deemed to have the greatest risk. The ORI allows you to rapidly develop an accurate outfall map and quantify the severity of your discharge problems. ORI data and field photos are extremely effective in documenting local problems. Stream walks and the ORI should be conducted regularly as part of an IDDE program. In many areas, it may require as many as three stream walks to identify all outfall locations.

*6. Use GPS to create your outfall map.* In most communities, the storm water system and sewer pipe networks are poorly mapped, and consist of a confusing blend of pipes and structures that were constructed in many different eras. Effective programs perform a field reconnaissance to ground truth the precise locations of all outfalls using GPS technologies. Effective programs have learned to quickly evaluate outfalls of all sizes, and not just major ones ( >36 inches in diameter).

*7. Understand your discharges before developing a monitoring plan.* Monitoring is usually the most expensive component of any local IDDE program, so it is extremely important to understand your discharges before committing to a particular monitoring method or tracer. Compiling a simple discharge "fingerprint" library that characterizes the chemistry of major flow types in the community (e.g., sewage, septage, washwater, groundwater, tap water, or non-target irrigation water) is recommended. This library can distinguish flow types and adjust monitoring benchmarks.

*8. Consider establishing an ambient (in-stream) chemical and/or biological monitoring program.* Prioritizing outfall screening and investigation can save time in the field. An ambient chemical or biological monitoring program can provide supplemental information to help prioritize sites and can be used to document long-term success.

*9. Utilize a simple outfall tracking system to organize all your IDDE program data.* Illicit discharges are hard enough to find if an organized system to track individual outfalls is lacking. Effective programs develop a unified geospatial tracking system to locate each outfall, and store information on its address, characteristics, photos, complaints and monitoring data. The tracking system should be developed early in the permit cycle so that program managers can utilize it as an evaluation and reporting tool.

*10. Outsource some IDDE functions to local watershed groups.* Staffing is the greatest single line item expense associated with a local IDDE program, although staffing needs are often temporary or seasonal in nature. Some effective programs have addressed this staffing imbalance by contracting with watershed groups to screen outfalls, monitor stream quality, and handle storm water education. This strategy reduces overall program costs, and increases local watershed awareness and stewardship.

*11. Utilize a hotline as an education and detection tool.* Citizen hotlines are a low-cost strategy to engage the public in illicit discharge surveillance, and are probably the only effective way to pick up intermittent and transitory discharges that escape outfall screening. When advertised properly, hotlines are also an effective tool to increase awareness of illicit discharges and dumping. Effective programs typically respond to citizen reports within 24 hours, acknowledge their help, and send them storm water education materials. When citizens play a stronger role in reporting illicit discharge problems, local staff can focus their efforts on tracing the problem to its source and fixing it.

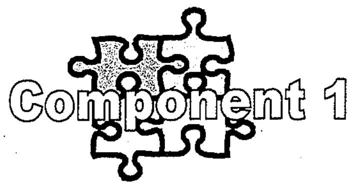
*12. Cross-train all local inspectors to recognize discharges and report them for enforcement.* Effective programs make sure that fire, building, plumbing, health, safety, erosion control and other local inspectors understand illicit discharges and know whom to contact locally for enforcement.

*13. Target your precious storm water education dollars.* Most programs never have enough resources to perform the amount of storm water education needed to reduce indirect and transitory discharges in their community. Consequently, effective programs target their discharges of concern, and spend their scarce dollars in the subwatersheds, neighborhoods or business sectors most likely to generate them.

*14. Stress public health and safety benefits of sewage-free streams.* Effective programs publicize the danger of sewage discharges, and notify the public and elected officials about the discharges that need to be prevented or corrected.

*15. Calibrate your program resources to the magnitude of the illicit discharge problem.* After a few years of analysis and surveys, communities get a good handle on the actual severity of their illicit discharge problems. In some communities, storm drains will be relatively clean, whereas others may have persistent problems. Effective programs are flexible and adaptive, and shift program resources to the management measure that will reduce the greatest amount of pollution.

*16. Think of discharge prevention as a tool of watershed restoration.* Discharge prevention is considered one of the seven primary practices used to restore urban watersheds (Schueler, 2004). Effective programs integrate illicit discharge control as a part of a comprehensive effort to restore local watersheds.




# Chapter 3: Auditing Existing Resources and Programs

*Purpose:* This program component identifies the most capable local agency to staff and administer the IDDE program, analyzes staffing and resource gaps, and searches for all available local resources and expertise that can be applied to the IDDE program.

*Method:* The key method used for this program component is a local IDDE "audit," which consists of external research, agency interviews, and interagency meetings to determine existing resources and program gaps. The audit typically looks at eight major factors needed to build an IDDE program:

- Profile of existing storm water and sewer infrastructure, as well as historical plumbing codes
- Existing legal authority to regulate illicit discharges
- Available mapping data and GIS resources
- Field staff availability and expertise
- Lab/monitoring equipment and analytical capability
- Education and outreach resources and outlets
- Discharge removal capability and emergency response
- Program budgeting and financing

*Desired Product or Outcome(s):* The desired outcome is an initial five-year IDDE program development plan over the current permit cycle. This will usually consist of an internal agreement on the lead agency, an initial scope of work, the first year budget, and a budget forecast for the entire permit cycle.

*Budget and/or Staff Resources Required:* The cost to conduct an audit depends on the size of the community, the degree of interagency cooperation, and the local budget process. Plan for less than one staff month for smaller communities, and up to three staff months for larger ones.

*Integration with Other Programs:* The audit is the best time to integrate the other five minimum management measures required under NPDES Phase II permits, including public education and outreach, public involvement, construction site runoff control, post-construction runoff control, and pollution prevention/good housekeeping for municipal operations.

## 3.1 Audit Overview

A community should conduct a quick audit of existing and needed capacity when developing its IDDE program. The audit helps develop realistic program goals, implementation strategies, schedules, and budgets to comply with NPDES permit requirements and improve water quality. The audit consists of external research, agency interviews and interagency meetings to determine existing resources and program gaps. The audit examines the community's current capabilities in eight topic areas: infrastructure profile, legal authority, available mapping, field staff experience, access to monitoring labs, education and outreach resources, discharge removal capability, and program budgets and financing.

Existing expertise is likely divided among multiple agencies (see Table 6) that should be contacted during the audit. Some of these agencies can become important partners in the development and implementation of the IDDE program, and contribute resources, program efficiencies and overall cost savings. The first agencies to interview are local emergency responders that already deal with spills, accidents, hazardous materials and sewage leaks that occur. In addition, it is worth getting to know the local agency responsible for plumbing code inspection during construction.

Table 7 provides representative examples of questions that the audit should ask to determine the needs and capabilities of a community associated with each program element.

**Table 6: Potential Local Agencies and Departments to Contact During an Audit**

| Audit Topic | Potential Agencies and Departments | |
|---|---|---|
| Infrastructure Profile | • Water and Sewer Authority | • Public Works |
| Existing Legal Authority | • Public Works<br>• Planning Department<br>• Parks and Recreation<br>• Environmental Protection | • Local Health Department<br>• Road Engineering<br>Fire, Police or Rescue (Hazardous material responders) |
| Available Mapping | • Public Works<br>• Local Streets/Utilities | • Planning and Zoning<br>• Emergency Responders |
| Field Staff | • Public Works<br>• Environmental Compliance<br>• Development Review | • Watershed Groups<br>• Fire, Building, Health and Code Inspectors |
| Access to Lab Services | • Public Works<br>• Local College or University | • Drinking Water or Wastewater Treatment Plant<br>• Private Contract Monitoring Laboratories<br>• Health Department |
| Education and Outreach Resources | • Parks and Schools<br>• Water and Sewer Utility | • Community Liaison Office<br>• Civic and Watershed Groups |
| Discharge Removal Capability | • Fire, Rescue and Police<br>• Public Works | • Water and Sewer Utilities<br>• Private Plumbing Contractors |
| Program Budget and Financing | • Grants<br>• Fines<br>• Application fees | • Utility Fees<br>• Department Operating Budget |



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**Table 7: Potential IDDE Audit Questions**

| Audit Topics | Questions |
|---|---|
| Infrastructure Profile | • How many miles of streams and storm drains exist in the MS4?<br>• What is the area served by storm drains, sewers, and septics?<br>• What is the general age and condition of the infrastructure? |
| Existing Legal Authority | • Does an illicit discharge ordinance already exist?<br>• Does effective inter-departmental coordination and cooperation currently occur?<br>• Is there an existing reporting and tracking system (e.g., hotline)?<br>• Is the municipality involved with industrial storm water NPDES permit activities or pre-treatment programs? |
| Available Mapping Data | • Does current GIS data exist and does it include coverage of sanitary and storm sewer networks?<br>• Is there a centralized location for the data?<br>• Are digital and hardcopy versions of mapping data readily available? |
| Field Staff | • Are municipal staff available to walk stream miles and record information?<br>• Do municipal staff have the training and expertise to lead a field team?<br>• Are basic field supplies already owned by the municipality and available for use? |
| Access to Lab Services | • Does the municipality have access to an analytical laboratory?<br>• Is there a local university or institution that might be a willing partner?<br>• If yes, is the existing equipment and instrumentation considered to be safe, accurate and reliable?<br>• Are experienced municipal staff available to conduct analytical analyses?<br>• Does the lab and staff have the capability to conduct more sophisticated special studies? |
| Education and Outreach Resources | • Does the community already have an Internet website to post outreach materials?<br>• Are there regular community events that can be used to spread the message?<br>• Are good inter-agency communication mechanisms in place?<br>• Do outreach materials on illicit discharges already exist? |
| Discharge Removal Capability | • Who currently responds to spills, overflows and hazardous material emergencies?<br>• Are municipal staff properly equipped and trained to repair most common types of illicit connections?<br>• Does the municipality have clear authority identifying responsible parties?<br>• Is there a response time commitment to known and reported problems?<br>• Is there a list of pre-approved contractors to perform corrections? |
| Program Budget and Financing | • Is there a dedicated annual budget line item planned for the IDDE program?<br>• Are there cost-share arrangements/opportunities available with other departments?<br>• Have grant awards been awarded to the municipality for special studies associated with watershed restoration in the past? |

## 3.2 Develop Infrastructure Profile

The first part of the audit profiles current and historic storm water and sewer infrastructure in the community. The basic idea is to get a general sense of the magnitude of the task ahead, by looking at the size, age and condition of the storm drain system (and the sewers within the MS4 as well). Some useful planning statistics include:

- Number of storm drain outfalls
- Miles of storm drain pipe
- Total stream and channel miles
- Total area serviced by storm drains
- Total area serviced by sewers
- Total area serviced by septic systems

These statistics are extremely helpful in getting a handle on the total effort required to assess the overall system. Any data on the nature and age of storm drains and sewers can be useful (e.g., open vs. enclosed, young vs. old). The basic infrastructure statistics can be generated from a quick analysis of infrastructure and topographic maps. At this stage, ballpark estimates are fine; more detailed estimates can be developed later in the desktop analysis component.

It is also worth examining historic plumbing codes to determine what kinds of connections were allowed in the past. Often, interviews with "old-timers" who remember past building codes and practices can provide insights about historical construction as to where illicit connections may be a problem.

## 3.3 Establish Legal Authority

This part of the audit examines whether a community currently has adequate legal authority to regulate illicit discharges through the following actions:

- Evaluate and modify plumbing codes[5]
- Prohibit illicit discharges
- Investigate suspected illicit discharges
- Require elimination of illicit discharges
- Carry out enforcement actions

The audit of existing legal authority entails a search and review of all existing ordinances that could conceivably bear on illicit discharge control, and interviews with the agencies that administer them. Some common local ordinances that may address illicit discharges are outlined in Table 8. Many communities already have regulations prohibiting specific illicit discharges, such as hazardous chemicals, litter or sewage. Often, public health ordinances may prohibit certain sewage discharges. Local utilities may have plumbing codes and staff capability to track down and remove illicit connections on the system they operate.

[5] In some states such as NC, plumbing codes are established through a state process. In these cases, local governments typically need specific authority to adopt any local modifications, which can be difficult to obtain. In such states, it may be prudent for the storm water program managers of several local governments to organize as a single cooperative group to modify codes at the state level.

**Table 8: Codes and Ordinances with Potential Links to IDDE**

| | |
|---|---|
| • Fire codes | • Pollution prevention permitting requirements |
| • Hazardous wastes / spill controls | • Restaurant grease regulations |
| • Health codes | • Septic system regulations |
| • Industrial storm water compliance | • Sewer / drain ordinances |
| • Litter control regulations | • Storm water ordinance |
| • Nuisance ordinances | • Street / highway codes |
| • Plumbing codes | |

To establish legal authority, communities will need to either develop a new IDDE ordinance or modify an existing ordinance that addresses illicit discharges. Language from existing ordinances that addresses illicit discharges should be incorporated or cross-referenced into any new IDDE ordinance to minimize conflicts and confusion. Furthermore, existing code ordinances may need to be amended or superceded to be consistent with the new IDDE ordinance.

In some instances, communities may want to consider collaborating with neighboring or nearby MS4s to develop ordinance language and legal authority, particularly if they share a common receiving water. Non-municipal permittees such as Departments of Transportation and special districts may also look to collaborate with municipal MS4s when considering ordinance language and legal responsibility.

## 3.4 Review Available Mapping

The third part of the audit looks at the coverage and quality of mapping resources available to support the IDDE program. Specifically, efforts should be made to see if a Geographic Information System (GIS) exists, and what digital mapping layers it contains. If a community does not possess a GIS, a community may choose to establish one (which can be quite expensive), or rely on available hardcopy maps. GIS and hardcopy maps are frequently available from the following local agencies: planning, tax assessment, public works, parks and recreation, emergency response, environmental, transportation, utilities, or health. If a watershed extends beyond the boundaries of a community, it may be necessary to acquire mapping data from adjacent communities.

Non-local sources of mapping data include state and federal agencies and commercial vendors. EPA and state environmental regulatory agencies maintain lists of NPDES dischargers; Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites; Resource Conservation and Recovery Act (RCRA) sites; and other industrial or hazardous material discharge sites. These sites are readily available as GIS layers[6]. Commercial vendors are good sources for low-altitude aerial photos of your community. These can be expensive but are often the best way to get a high-resolution recent 'snapshot' of the jurisdiction. Chapter 5 presents more detail on mapping layers needed for an IDDE program.

## 3.5 Availability of Field Staff

Field staff play a critical role in any IDDE program as they walk streams, assess outfalls, collect samples, respond to discharge complaints, and handle enforcement. This part of the audit evaluates

[6] Some readily available GIS layers provided by regulatory agencies can be incomplete and inaccurate (particularly with location information). Communities should use their IDDE program and the associated data collection efforts to update their local information associated with these databases.

the availability of local staff to perform these functions, and their training needs. Phase I communities report that experienced field staff are a major factor in IDDE program success.

Experienced staff can be supplemented with support staff such as interns and local watershed groups, if they are properly trained (CWP, 2002). As part of the audit, program managers should investigate whether existing staff can be used or whether new hires are anticipated, and explore intern opportunities with local universities and community colleges. Any local staff with experience in water quality sampling or development inspection should be identified. Fire, building, health, safety and erosion control inspectors are all potential field crew draftees.

An initial estimate of the staff time needed for field crews should be made at this time. Phase I IDDE programs allocated a median of 1.0 person-year for field investigations, with a range of 0.1 to 10 person-years each year (CWP, 2002). Several communities utilized interns to assist with field monitoring and office work. Since many IDDE surveys are short term and seasonal, several communities hired or transferred employees to serve on field crews on a temporary basis. Many Phase I programs found it hard to precisely quantify actual staff time dedicated to IDDE field work because staff were assigned from many departments, or performed other unrelated tasks (building inspections, erosion and sediment control inspections, etc.).

## 3.6 Access to Laboratory Analysis

This part of the audit identifies the best options for laboratory analysis of water quality samples collected in the field. Four basic options exist to get access to laboratory services, including:

1. Contract services from a private lab
2. Use existing lab facilities at local drinking water or wastewater treatment plants
3. Partner with a local water and sewer district, university or community college
4. Develop your own "in-house" monitoring and lab capability

The last three options may require purchasing special monitoring analysis equipment, depending on the water quality indicators ultimately selected. If a community is considering developing "in-house" monitoring capabilities, it will need to address quality control, training needs, safety, and hazardous waste disposal. At this point, a community simply wants to acquire data on costs, indicator parameters, quality control, and experience for each of the options being evaluated. Chapter 12 provides more detail on factors to consider when selecting lab analysis options.

## 3.7 Education and Outreach

The next part of the audit looks at existing educational and outreach resources in the community. To begin, look for other groups that are already involved in storm water or watershed education, including parks, schools, watershed groups, utilities and any other agencies performing this role. Next, look for the current tools the public can use to report water quality problems, such as complaint hotlines, websites or community liaison offices. When these exist, it may be possible to "piggy back" illicit discharge reporting at little additional cost. If reporting tools do not exist, program managers should look for opportunities to share start-up costs with other agencies that may stand to benefit from improved community interaction (e.g., erosion and sediment control, sanitary sewer overflows, abandoned cars, etc.).

The audit should also look at community-wide events and education outlets to spread the IDDE message, such as fairs, festivals, earth day events, school presentations, and homeowner association meetings. For a complete review of how to craft an effective outreach and education plan, consult Pollution Source Control Practices (Schueler *et al.*, 2004). Excellent education and outreach materials have already been developed by Phase I communities that are available at little or no cost (see Chapter 9). Program managers should consult these resources and modify them as needed to meet their local needs.

## 3.8 Discharge Removal Capability and Tracking

This part of the audit evaluates local capacity to locate specific discharges, make needed corrections or repairs, and take any enforcement actions. These responsibilities are frequently split among several local agencies. For example, spills are often handled by the fire department hazmat response team, whereas dumping may be enforced by public works. Communities should always coordinate their IDDE program with any experienced hazmat response teams that exist. Similarly, local water and sewer utilities or private contractors that are in the business of repairing pipes should always be consulted. Their experience in specialized techniques such as dye or video testing of pipe interiors is essential for many illicit discharge source investigations. Alternatively, communities can opt to contract out many of these services.

Illicit discharges often occur due to "bad plumbing" connections. Therefore, the audit should identify key building inspectors to determine what, if any, procedures are in place to prevent these deficiencies. Lastly, where corrections to plumbing are required, communities should maintain a list of "pre-approved" plumbing contractors that can promptly and professionally repair the problem.

To ensure coordination, an up-to-date tracking system should be shared among all agencies involved.

## 3.9 Program Funding

The last part of the audit explores how much the local IDDE program will cost, and how it will be funded. This section provides some general budgeting guidance on the costs to expect for the eight program components. Overall IDDE program costs vary depending on the severity of the illicit discharge problem, the size of the community (and storm drain systems), and the IDDE program choices you make.

Planning level budget estimates can be derived for the eight IDDE program components in three ways. The first way is to look at the cost of IDDE program compliance for Phase I NPDES communities. These costs were assessed in a CWP (2002) survey, and can be used to budget overall annual costs for an IDDE program. Table 9 summarizes median program costs for selected Phase I IDDE program activities. The second technique is to construct unit cost budgets for each program component, based on an assumed level of effort. The third technique relies on EPA's overall average estimate of compliance costs for Phase II IDDE program of $1.30 per capita (with a staggering range $0.04 to $2.61/capita).

### Phase I IDDE Program Costs

The bulk of the cost for most IDDE programs is related to staffing – typically, about 75% of the total budget. Equipment costs were fairly reasonable, with programs spending a median of $1,000 on office computers and software, and about $4,000 on field equipment. Many equipment costs can typically be shared across other community programs. Lab costs, for either the purchase of lab equipment or the cost associated with sending samples to labs, were as high as $87,000 annually, with a median of $8,000. Finally, most programs had additional budgets for "other" which included items such as education, training, travel, consultants, and contractors.

It is worth noting that program costs presented in Table 9 do not reflect expenditures associated with special investigations, which may be pursued by communities to isolate specific sources or test new methods or the direct costs to fix problem connections. However, five communities provided data on typical correction costs, with an average cost of $2,500 per correction (Table 10).

### Estimated Phase II IDDE Program Unit Cost

Cost estimates for the eight IDDE program components are outlined in Table 11; more detailed guidance on budgeting for individual program components is provided in subsequent chapters. Under this presentation of cost, data, staff, equipment, and supply costs are combined and incorporated into a primary program element, such as conducting an outfall reconnaissance inventory. This approach assumes a hypothetical scenario of stream/MS4 miles and outfalls to investigate (see Table 11 notes).

**Table 9: Summary of Annual Phase I IDDE Program Costs**

| Program Element | Median Annual Cost |
|---|---|
| Staff | $85,100 |
| Office Equipment (Computer/Software) | $1,000 |
| Field Equipment | $4,000 |
| Lab Equipment/Testing | $8,000 |
| Other | $10,000 |
| **Total** | **$121,825** |

**Table 10: Average Correction Costs**

| Jurisdiction | Average Cost Per Correction |
|---|---|
| Cambridge, MA | $5,000 |
| Boston, MA | $3,570 |
| Knoxville, TN | $2,000 |
| Raleigh, NC | $1,000 |
| Springfield, MO | $1,000 |
| **Average** | **$2,500** |

| Table 11: IDDE Program Costs | | | | | |
|---|---|---|---|---|---|
| IDDE Program Component | | Start Up Cost | | Annual Cost | |
| | | Low | High | Low | High |
| Component 1: | a) Perform Audit | $3,000 | $9,000 | NA | NA |
| | b) Initial Program Plan | $1,000 | $3,000 | NA | NA |
| Component 2: | a) Adopt Ordinance | $1,000 | $17,000 | NA | NA |
| | b) Tracking System | $2,000 | $15,000 | $2,000 | $2,000 |
| Component 3: | a) Desktop Analysis | $1,000 | $4,000 | NA | NA |
| | b) Field Mapping | $500 | $1,000 | NA | NA |
| Component 4: | a) Develop Goals | $1,000 | $3,000 | NA | NA |
| | b) Field Monitoring Strategy | $1,000 | $3,000 | NA | NA |
| Component 5: | a) Outfall Reconnaissance Inventory (ORI) | NA | NA | $5,700 | $12,800 |
| | b) Establish Hotline | $1,300 | $7,700 | $1,500 | $11,400 |
| | c) Sample Analysis | $500 | $15,500 | $9,000 | $21,200 |
| | d) Outfall Map | NA | NA | $500 | $1,000 |
| Component 6: | a) Isolate | NA | NA | $2,000 | $5,200 |
| | b) Fix | NA | NA | $10,000 | $30,000 |
| Component 7: | a) Education | $1,000 | $8,100 | $1,300 | $13,900 |
| | b) Enforcement | NA | NA | $1,000 | $14,000 |
| Component 8: | a) Program Administration | $10,000 | $15,000 | $10,000 | $15,000 |
| **TOTAL** | | **$23,300** | **$101,300** | **$43,000** | **$126,500** |

*Notes*: NA = Not Applicable

Component 1 – Audit assumes $25/hr, 120 hours for low and 360 hrs for high. Program plan assumes 40 hrs for low and 120 hrs for high.

Component 2 – Ordinance low cost from Reese (2000), high cost from CWP (1998) adjusted and rounded for inflation (2002 $). Tracking system low cost assumes 40 hrs of development and $1K of equipment for start up. Annual cost for low assumes 40 hrs per year. High estimates are adapted from Reese (2000) and assume 200 hrs for development and $3k for equipment at start-up. High annual costs assume 100 hrs per year.

Component 3 – Desktop analysis assumes 1 week for low and 4 weeks for high. Mapping costs assume paper maps (CWP, 1998) under low and GIS under high (40 hrs)

Component 4 – Goals and strategies take 2 weeks for low and 6 weeks for high. Assume even split in time between two tasks.

Component 5 –
a) ORI costs are from Ch 11 and assume 10 miles with 2-person crew for low and 20 miles with 3-person crew for high. ORI costs assume work completed in one year, but not necessarily every year (permit cycle cost).
Low hotline costs are adapted from Reese (2000). High costs are from CWP research. Low annual costs assume an increased volume of calls due to advertisement and assume 50 hours per year dedicated to this plus annual training.
Sample analyses are from various sources and are presented in Chapter 12. Estimates based on 80 samples per year for both (shown as annual cost). Low start up costs are based on contract lab arrangements. High start up costs assume flow type library is developed for eight distinct flow types. Low annual costs assume in-house analysis for Flow Chart Method parameters. High annual costs assume contract lab analysis for 11 parameters.
Outfall map costs are same as the component 3 mapping task

Component 6 – Isolate and fix have no assumed start up costs and are both vary depending on the community conditions. Low annual isolation costs assume a one day investigation by a 2-person team per incident ($400) and four incidents per year plus $400 in equipment and supplies. High assumes one incident per month. Estimates include on-site inspections. Fix costs are from average costs from Phase I survey and assume same number of incidents as isolate. These costs can often be passed on to responsible parties.

Component 7 – Education estimate adapted from Reese (2000) and assumed to be 1/3 of total Phase I education budget. Some adjustments were made based on assumptions by CWP.

Component 8 – Low assumes 1/6 FTE, high assumes 1/4 FTE at an annual salary of $60K.

### *Financing an IDDE Program*

Once the initial budget has been estimated, the next step is to investigate how to pay for it. A full discussion of how to finance local storm water management programs is beyond the scope of this manual, but it is worth consulting APWA (2001). The most common financing mechanisms include:

- Operating budgets
- Debt financing
- State grants and revolving loans
- Property assessments
- Local improvement districts
- Wastewater utility fees
- Storm water utility or district fees
- Connection fees
- Plan review/inspection fees
- Water utility revenues

Of these, storm water utilities or districts are generally considered one of the best dedicated financing mechanisms. Some useful resources to consult to finance your local storm water programs include the following:

- An Internet Guide to Financing Storm Water Management. 2001 http://stormwaterfinance.urbancenter.iupui.edu
- Establishing a Storm Water Utility http://www.florida-stormwater.org/manual.html
- Florida Association of Storm Water Utilities. http://www.fasu.org
- How to Create a Storm Water Utility http://www.epa.gov/nps/urban.html
- The Storm Water Utility: Will It Work in Your Community? www.forester.net/sw_0011_utility.html

## 3.10 The Initial IDDE Program Plan

The local IDDE audit reveals resource gaps, and expertise and staffing needed to build an effective IDDE program. The next step is to organize how you plan to phase in the eight program components over the permit cycle. The process results in the development of an initial IDDE program plan that normally includes five elements:

- Overall schedule for plan implementation, with milestones
- Detailed work plan for the first year
- Budget for the first year
- Five-year budget forecast
- Process for gaining approval for first-year budget

Program managers should consult the next seven chapters for more guidance on planning and budgeting individual IDDE program components.

# Chapter 4: Establishing Responsibility and Legal Authority

*Purpose:* This program component is where the legal and administrative authority is established to regulate, respond and enforce illicit discharges in the community. The component also reviews local plumbing codes to ensure that inappropriate connections are prohibited, and develops a tracking system to locate illicit discharges and track management response.

*Method(s):* Several methods are used to implement this program component, including development of a new or amended illicit discharge control ordinance and the creation of a relational computer database for internal and external tracking of illicit discharges.

*Desired Product or Outcome(s):*

a) Pass or amend a local ordinance that defines the lead regulatory agency, defines the range of illicit discharges to be covered, and specifies the range of enforcement mechanisms.

b) Establish an internal and external reporting and tracking system. The internal system is structured around the training/education of municipal staff to define and facilitate appropriated response and enforcement procedures. An external system or hotline links to the internal system and assists in response and enforcement by providing access to the public for reporting.

*Budget and/or Staff Resources Required:* Establishing responsibility, legal authority and an effective tracking system can take as little as a month of staff effort to complete if no major surprises or unforeseen costs are encountered in the process. However, the actual time-frame to adopt an ordinance or fund a response system, for example, is often much longer, given the crowded schedules of elected officials and timing of the local budget processes. Adoption of the ordinance and the actual budget authorization may require multiple votes over many months or years. Continuous engagement and education of key advisors, agency staff and elected officials are needed throughout the effort. Where hotlines exist (covering a range of municipal functions), significant staff and infrastructure savings should be realized. The primary hurdle in this instance will be employee training and education.

*Integration with Other Programs*: Public education to advertise the hotline and municipal training to educate employees across departments and agencies are the primary areas where this program component can be integrated with other community-wide initiatives. The hotline can be used to report other watershed and water quality problems (e.g., ESC, dumping, sanitary sewer overflows). Good coordination should occur between tracking repair costs and determining appropriate fine levels for enforcement purposes.

Three critical decisions are needed to implement this program component—what local agency will be responsible for administering the IDDE program, will it have adequate legal authority to do its job, and how will illicit discharges be tracked. Guidance is offered below to help program managers make these decisions.

## 4.1 Identify Responsible Department/Agency

For most communities, the IDDE program will be established under the same agency or department that oversees all other MS4 NPDES requirements (e.g., Department of Environmental Protection, Department of Public Works, Department of Health, etc.). For small communities, IDDE program administration and implementation may be wrapped into the broad duties of just a few staff. For larger communities, or where there are significant known problems associated with illicit discharges, a community may elect to have a dedicated department division with core staff. In either event, the agency and individuals responsible for the program should be well identified along with a clear understanding of program purpose, goals and actions.

Other local departments may already have authority over certain aspects of illicit discharges. Therefore, close coordination and communication with different departments is essential, and consideration should be given to consolidating responsibilities and authority. If consolidation is not pursued, regular inter-departmental briefings, training sessions, and data sharing will enhance program effectiveness and reduce the likelihood of significant lag times between discovery of a discharge and enforcement or correction due to split responsibilities between departments.

In some cases, communities may want to consider collaborating with adjacent or nearby permittees in order to form a regional approach to addressing illicit discharges. This might be appropriate in situations where municipalities share a common receiving water, and program implementation is conducted on a watershed management basis.

## 4.2 Develop Local Illicit Discharge Ordinance

A community must demonstrate that it has adequate legal authority to successfully implement and enforce its IDDE program. In fact, establishing legal authority is one of the required components identified in Phase II regulations, and can be identified as a measurable goal. Guidance is provided below on how to develop an IDDE ordinance to establish legal authority.

### *Reviewing What You Have*

Communities with illicit discharge prohibitions in place have typically invoked legal authority using one or more of three mechanisms:

1. Storm water ordinance that prohibits illicit discharges to the drainage network
2. Plumbing code that prohibits illicit connections to the drainage network
3. Health code that regulates the discharge of harmful substances to the drainage network

A few concerns arise with the second and third mechanisms. One example is plumbing codes that only prohibit illicit connections fail to address other common discharges, such as indirect discharges, illegal dumping, or failing infrastructure. Similarly, exclusive reliance on health codes to regulate illicit discharges may not pick up discharges that are not harmful to human health, such as groundwater or potable water infiltration and residential irrigation return flows. With some revision and expansion, one or all of these existing mechanisms can meet the needs of the IDDE program. Alternatively, a new, stand-alone illicit discharge ordinance can be developed that supercedes all other related codes.

**CASE STUDY**

The City of Raleigh is an NPDES Phase I community. The Water Quality Group (WQG) within the Public Works Department oversees the City's illicit discharges program. The WQG was created in the early 1990s to be responsible for surface water quality across the City and to ensure compliance with the City's NPDES permits. Prior to that, various departments within city government handled water quality issues.

Raleigh's Illicit Discharge Ordinance was adopted in the second year of their original NPDES Phase I permit. The ordinance clearly defines and prohibits illicit discharges and illicit connections; requires containment and clean-up of spills/discharges to, or having the potential to be transported to, the storm drain system (it is also standard operating procedure that the City fire chief be notified of any spills immediately); allows for guaranteed right of entry for inspection of suspected discharges and connections; and outlines escalating enforcement measures, including civil penalties, injunctive relief, and criminal penalties.

Although the WQG runs the IDDE program, some functions are undertaken by the City's Public Utilities Department (e.g., fixing problems in the sanitary line, conducting dye and smoke testing, television inspection of the lines).

Raleigh began with a flat annual IDDE budget based on their past experience of what the program costs to run. More recently, the program began receiving additional funds from the City's storm water utility. A portion of the budget is allocated for testing. Cleaning and correction costs are funded through various budgets depending on the illicit discharge source. The WQG also budgets for two specialists: one is responsible for enforcement and dealing with citizen complaints and the other is responsible for monitoring and tracing the source of problems. The cost of television inspection and smoke testing is included in the Public Utilities Department budget.

*Source: Senior (2002, 2004)*

The length and complexity of an IDDE ordinance is largely a local community decision. Appendix B provides a model ordinance that may be adapted to meet the specific needs of local communities.

Some key components that should be addressed to ensure full authority to prevent and correct illicit discharges include the following:

- Prohibit illicit discharges
- Investigate suspected illicit discharges
- Require and enforce elimination of illicit discharges
- Address unique conditions or requirements

## Defining What is Illicit

An IDDE ordinance should clearly define and/or identify illicit discharges and clearly state that these discharges are prohibited. Some communities may prefer to provide a short, concise definition of illicit discharges, while others may wish to list specific substances or practices that qualify as illicit discharges. However, if a detailed list is provided in the ordinance, a qualifying statement should follow in order to include polluting discharges not specifically listed.

Illicit connections should also be defined in the ordinance. These connections include pipes, drains, open channels, or other conveyances that have the potential to allow an illicit discharge to enter the storm drain system. The prohibition of illicit connections should be retroactive to include connections made in the past, whether or not the connection was permissible at the time. This is especially important if historic plumbing codes or standards of practice allowed for connection of laterals and drains (e.g., shop floor drains) to the MS4.

Lastly, the ordinance should identify categories of non-storm water discharges or other flows to the MS4 that are not considered illicit. For example, the Phase II rule exempts discharges resulting from fire fighting activities. Other activities that are commonly exempt include discharges from dye testing and non-storm water discharges permitted under an NPDES permit, provided that the discharger is in full compliance with the permit. The following categories of non-storm water discharges do not need to be addressed in the IDDE program unless the operator of the regulated small MS4 designates them as significant contributors of pollutants:

- Water line flushing
- Landscape irrigation
- Diverted stream flows
- Rising ground waters
- Uncontaminated ground water infiltration
- Uncontaminated pumped ground water
- Discharges from potable water sources
- Foundation and footing drain water
- Air conditioning condensation
- Irrigation water
- Springs
- Water from crawl space pumps
- Lawn watering
- Individual residential car washing
- Flows from riparian habitats and wetlands

In some cases, communities will need to assess unique local discharges of concern and ensure that they are properly addressed within the ordinance. Examples of unique conditions or requirements sometimes included in IDDE ordinances are septic system provisions, plumbing codes, point of sale dye testing, and pollution prevention plan requirements for certain generating sites.

## Provisions for Access and Inspection

Although many communities report that most property owners cooperate when asked for access for illicit discharge investigations, this should never be taken for granted. Indeed, the right of access to private property for inspections is an essential provision of any IDDE ordinance. The ordinance should provide for guaranteed right of entry in case of an emergency or a suspected discharge or at any time for routine inspections, such as dye or smoke tests.

The ordinance should also clarify that right of entry applies to all land uses in the community, and that proof of discharge is not required to obtain entry. It should also state the responsibility of the property owner to disarm security systems and remove obstructions to safe and easy access. Enforcement actions should be established for property owners that refuse access, including the ability to obtain a search warrant through the court system.

### Types of Enforcement Tools

An IDDE ordinance should define a range of enforcement tools so the responsible agency can effectively handle the wide range of illicit discharge violations it is likely to encounter. Potential enforcement tools can range from warnings to criminal prosecution. The choice of enforcement tools should be based on volume and type of discharge, its impact on water quality and whether it was intentional or accidental. In addition, it is helpful to spell out the specific activities that trigger progressively greater enforcement. Table 12 summarizes the range of enforcement tools that have been used by communities to respond to illicit discharges.

The ordinance should provide for escalating enforcement measures to notify operators of violations and to require corrective action. Voluntary compliance should be used for first-time, minor offenders, while more serious violations or continued non-compliance may warrant a more aggressive enforcement approach. Finally, the ordinance should include methods for appeal to provide owners with avenues for compliance.

### Establish a Tracking and Reporting System

Communities need to develop tracking and reporting systems to support the entire IDDE program, including enforcement. A relational database with geospatial features provides the greatest flexibility to cover multiple program objectives. From a legal standpoint, tracking systems are important for historical documentation of problems and corrective actions. More details on designing and operating a tracking system are described in subsequent chapters.

| Table 12: Summary of IDDE-Related Enforcement Tools | |
|---|---|
| **Type of Enforcement Action** | **Description** |
| Written Warning with Voluntary Compliance | • Applies to first time, minor violations (Field staff should have authority to do this) |
| Written Notice of Violation Ordering Compliance | • Should clearly state description of remedial measures necessary, time schedule, penalties assessed if it doesn't happen, and timeframe for appeal |
| Administrative Penalties | • Daily financial penalty imposed by a responsible department for each day violation remains unfixed |
| Civil Penalties | • Daily financial penalty imposed by judicial authority for each day violation remains unfixed |
| Compensatory Action | • In lieu of enforcement proceedings or penalties, impose alternative compensatory action, e.g., storm drain stenciling, etc. |
| Criminal Prosecution | • Applies to intentional and flagrant violations of ordinance<br>• Each day discharge continues is typically a separate offense<br>• Can result in fines and imprisonment |
| Cost of Abatement of the Violation / Property Liens | • Applies when jurisdiction remedies the discharge or conducts cleanup, but may also be used to recoup administrative costs<br>• May constitute a property lien if not paid within certain timeframe |
| Emergency Cease and Desist Order | • Applies when ordinance continues to be violated<br>• Requires immediate compliance with ordinance by halting operations/ terminating discharges<br>• May be a written or verbal order to remove illicit discharge |
| Suspension of Water or Sewer Service | • Applied in emergency situations to immediately discontinue discharge to MS4<br>• May be applied as enforcement measure when property owner does not comply / fix the problem within timely manner |
| Stop Work Order | • Typically applies to discharges associated with construction activity<br>• No further work can be done until compliance is achieved |

# Chapter 5: Desktop Assessment of Illicit Discharge Potential

*Purpose*: This program component uses mapping and other available data to determine the potential severity of illicit discharges within a community, and identifies which subwatersheds or generating land uses merit priority investigation.

*Method(s)*: A simple desktop assessment method can rapidly determine the severity of illicit discharge problems in a community. If an MS4 has fewer than 20 stream miles, this component can be skipped and a community can proceed directly to an ORI. The desktop assessment method has five basic elements:

1) Delineate subwatersheds or other drainage units within your community
2) Compile available mapping and data for each drainage unit (e.g., land use, age, outfalls, infrastructure history)
3) Derive subwatershed discharge screening factors using GIS analysis
4) Screen and rank illicit discharge potential at the subwatershed and community level
5) Generate maps to support field investigations

*Desired Product or Outcome(s)*: The desktop assessment is used to guide initial field screening, and support initial IDDE program decisions. Key outcomes include:

a) Screening problem catchments or subwatersheds
b) Creation of GIS or other database system to track outfalls
c) Gaining an overall assessment as to the severity of illicit discharge problems in the community
d) Generation of basic mapping for subsequent field work

*Budget and/or Staff Resources Required:* The initial desktop assessment of illicit discharge potential should not be a long or arduous process, and should generally take less than four staff weeks. The quality and accuracy of the desktop assessment, however, will vary depending on the extent of available mapping information and GIS data. If mapping information is poor, the desktop assessment should be skipped, and program managers should go directly to the field to inventory outfalls.

*Integration with Other Programs:* If the desktop assessment suggests few potential illicit discharge problems, program managers may want to combine outfall surveys with broader stream corridor assessment tools such as the Unified Stream Assessment (Kitchell and Schueler, 2004). The desktop assessment provides insight on how to narrow your illicit discharge search, and is helpful when designing a discharge tracking system to best suit your needs. Finally, the desktop assessment can identify subwatersheds, generating sites, and neighborhoods where storm water education should be targeted to address illicit discharge problems.

## 5.1 Overview of Desktop Assessment of Illicit Discharge Potential

A community should understand the extent of water quality problems caused by illicit discharges. The desktop assessment should not be a time-consuming research effort, but should draw on existing background data and anecdotal information to initially characterize illicit discharge potential at the subwatershed level.

Subwatersheds are then screened based on their composite score, and are designated as having a low, medium or high risk:

- Low – no known illicit discharge problems in the subwatershed
- Medium– problems are confined to a few stream reaches, outfalls or specific generating sites in the subwatershed
- High – Problems are suspected to be severe throughout the subwatershed.

The desktop assessment also shapes the overall direction of a local IDDE program. For example, if the desktop assessment indicates that the risk of illicit discharges is low in the community, program managers may want to shift resources to other minimum management measures and integrate them into a broader watershed assessment and restoration effort. For example, IDDE programs may emphasize storm water education, public involvement and hotline setup. By contrast, if the desktop assessment reveals significant potential for severe discharges, program managers will need to allocate significant program resources to find and fix the discharge problems.

The recommended scale for desktop assessments is the subwatershed or sewershed, which typically range from two to 10 square miles in area. These small planning units are easily delineated on maps or a GIS system. Next, mapping, monitoring and other data are analyzed to identify subwatersheds with the greatest potential to contribute illicit discharges. The sophistication of the analysis varies depending on the data available, but can encompass up to 10 different screening factors. The desktop assessment consists of five basic steps:

Limited mapping or data should not hinder a desktop assessment. Most communities will have some gaps, but should make the most out of what they have. The desktop assessment is an office exercise to locate the most promising subwatersheds to find illicit discharge; subsequent outfall screening is needed to discover the problem outfalls in the field.

Step 1: Delineate subwatersheds

Step 2: Compile mapping layers and subwatershed data

Step 3: Compute discharge screening factors

Step 4: Screen for illicit discharge potential at the subwatershed and community level

Step 5: Generate maps to support field investigations

### *Step 1: Delineate Subwatersheds*

Since hundreds of outfalls and many stream miles exist in most communities, the MS4 should be divided into smaller, more manageable planning units known as subwatersheds. If the community already does watershed planning, these subwatersheds may already be delineated, and should be used for subsequent characterization and screening. Working at the subwatershed scale is usually the most efficient way to conduct both desktop assessments and field surveys.

In small, heterogeneous or densely developed MS4s, conducting the assessment on a smaller scale may be more effective. In this case, sewersheds or catchments that are less than one square mile in area and have a common outfall or discharge point should be delineated. This finer level delineation allows for a refined characterization that can pinpoint probable sources of illicit discharges, but can obviously consume a lot of time. It should be noted that sewersheds do not always follow topographic delineations and therefore can provide a more accurate picture of the contributing areas to a particular outfall.

If subwatersheds are not yet defined, hydrologic, infrastructure and topographic map layers are needed to delineate the boundaries. Guidance on the techniques for accurately delineating subwatershed boundaries can be found at www.stormwatercenter.net (click "Slideshows," then scroll down to "Delineating Subwatershed Boundaries"). The use of digital elevation models (DEMs) and GIS can also make subwatershed delineation an easier and faster, automated process.

Some subwatersheds extend beyond the political boundaries of a community. Where possible, it is recommended that the entire subwatershed be delineated and assessed in conjunction with neighboring municipalities. This helps to ensure that all potential sources of illicit discharges are identified in the subwatershed, regardless of the community from which they originate.

### *Step 2: Compile Mapping Layers and Subwatershed Data*

Once subwatersheds (or catchments) are delineated, a community can begin to acquire and compile existing data for each drainage area, preferably with a Geographic Information System (GIS). A GIS allows the user to analyze and manipulate spatial data, rapidly update data and create new data layers, associate data tables with each map layer, and create paper maps to display subwatershed information. A GIS can greatly speed up data compilation and provides greater accuracy in mapping specific locations. The mapping information facilitates the interpretation and understanding of the discharge screening factors (Step 3).

If a community does not currently have a GIS, developing a system from scratch may seem daunting, however, most GIS software can be installed on basic PCs, and free GIS data layers are often available online. The basic elements of a GIS program include a PC, Global Positioning System (GPS) units, a plotter, a digitizer, GIS software, data and staff training. As with many technologies, both low-end and high-end versions are available, as are many add-ons, extensions and tools. While a GIS is not necessary for the IDDE desktop assessment, it does make the process more efficient and accurate, which can save money in the long run. Moreover, other agencies within a community usually need or use GIS and may be willing to share hardware, software, support and development costs[7].

Acquiring data for each subwatershed is the next step in the desktop assessment process.

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[7] If a community plans to defer using GIS, all databases it develops should have location information suitable for later use with GIS (i.e., using suitable georeferencing technology such as GPS).

The extent and quality of the data available for mapping directly influence subsequent analyses and field investigations. A list of recommended data layers to acquire for the desktop assessment is provided in Table 13.

Some mapping data may exist in GIS format, whereas others are only available in digital or hardcopy formats that need to be converted to GIS. Digital data with a geo-spatial reference such as latitude and longitude, parcel ID numbers or addresses can be directly entered into a GIS, if an existing road or parcel GIS layer can be associated to it. Hardcopy maps can also be digitized to create new GIS data layers. This can be a labor-intensive process, but will only need to be done once and can be easily updated. If GIS is not an option, hardcopy maps and data can be analyzed, with an emphasis on tax maps, topographic maps, historic aerial surveys, and storm drain and outfall maps.

Most data layers can be obtained from local sources, such as the city planning office, emergency response agency, or public works department. If a subwatershed extends beyond the boundaries of your community, you may need to acquire data from another local government. Some data layers may be available from state and federal agencies and commercial vendors. EPA and most state environmental agencies maintain databases of industrial NPDES, CERCLA, RCRA and other sites that handle or discharge pollutants or hazardous materials. These searchable permit databases are often available as GIS layers (see Appendix A). Commercial vendors are good sources for low-altitude aerial photos of your community. Aerial photos can be expensive but are often the best way to get a recent high-resolution 'snapshot' of subwatershed conditions.

**Table 13: Useful Data for the Desktop Assessment**

| | Data | Likely Format |
|---|---|---|
| Recommended | Aerial photos or orthophotos | Digital map |
| | Subwatershed or catchment boundaries | Digital or hardcopy map |
| | Hydrology including piped streams | Digital or hardcopy map |
| | Land use or zoning | Digital or hardcopy map |
| | NPDES storm water permittees | Digital data or map |
| | Outfalls | Digital or hardcopy map |
| | Sewer system, 1" = 200' scale or better | Digital or hardcopy map |
| | Standard Industrial Classification codes for all industries | Digital or hardcopy data |
| | Storm drain system, 1" = 200' scale or better | Digital or hardcopy map |
| | Street map or equivalent GIS layers | Digital or hardcopy map |
| | Topography (5 foot contours or better) | Digital or hardcopy map |
| Optional | Age of development | Narrative data |
| | As-builts or construction drawings | Hardcopy map |
| | Condition of infrastructure | Narrative data |
| | Field inspection records | Hardcopy or digital data |
| | Depth to water table and groundwater quality | Digital data or maps |
| | Historical industrial uses or landfills | Narrative data or hardcopy map |
| | Known locations of illicit discharges (current and past) | Narrative data or digital map |
| | Outfall and stream monitoring data | Digital data |
| | Parcel boundaries | Digital or hardcopy map |
| | Pollution complaints | Narrative data |
| | Pre-development hydrology | Narrative data or hardcopy map |
| | Sanitary sewer Infiltration and Inflow (I/I) surveys | Hardcopy or digital data |
| | Septic tank locations or area served by septic systems | Hardcopy or digital map |
| | Sewer system evaluation surveys | Hardcopy or digital data |

Alternatively, TerraServer (http://terraserver.microsoft.com/default.aspx) is a free mapping resource that most communities can use to get good quality aerial and other coverages (Figure 8 is an example). Higher quality photos may be desirable as more detailed investigations are pursued.

As GIS technology has become more affordable and easier to use, Phase II communities should harness their capabilities to develop the storm sewer system maps required by NPDES permits. GIS can become a powerful tool to track and manage the entire IDDE program, and demonstrate compliance in annual reports. In addition to being a powerful tool for analysis, GIS is also a great tool for communicating with the public. The images that can be created with GIS can summarize tables of data in a way that the public appreciates. If the recommended data layers are not available, a community may want to devote program resources to create or obtain them. Once data layers have been collected and digitized, they can be entered into the GIS to create a map of each subwatershed (Figure 8). Make sure all data layers are in the same coordinate system, and perform any conversions needed. Clip data layers to subwatersheds to enable calculation of factors such as land use, area, and outfall density. Summary data on subwatershed water quality and statistics on the age and condition of infrastructure should be entered into a database created for analysis in the next step.

### *Step 3: Compute Discharge Screening Factors*

The third step of the desktop assessment defines and computes discharge factors to screen subwatersheds based on their illicit discharge potential (IDP). As many as 10 different discharge screening factors can be derived during the screening process, but not all may apply to every community. The potential screening factors are described in Table 14, along with how they are measured or defined. Keep in mind that these screening factors are a guide and not a guarantee. Each screening factor is described in detail in the following section.

**Figure 8: GIS Layers of Outfalls in a Subwatershed**
*Markings illustrate Tuscaloosa, AL outfalls and drainage areas surveyed as part of this project.*

| Table 14: Defining Discharge Screening Factors in a Community | |
|---|---|
| Discharge Screening Factors | Defining and Deriving the Factor |
| 1. Past Discharge Complaints and Reports | Frequency of past discharge complaints, hotline reports, and spill responses per subwatershed. Any subwatershed with a history of discharge complaints should automatically be designated as having high IDP. |
| 2. Poor Dry Weather Water Quality | Frequency that *individual* samples of dry weather water quality exceed benchmark values for bacteria, nutrients, conductivity or other predetermined indicators. High risk if two or more exceedances are found in any given year. |
| 3. Density of Generating Sites or Industrial NPDES Storm Water Permits | Density of more than 10 generating sites or five industrial NPDES storm water sites per square mile indicates high IDP. Density determined by screening business or permit databases (Appendix A). |
| 4. Storm Water Outfall Density | Density of mapped storm water outfalls in the subwatershed, expressed as the average number per stream or channel mile. A density of more than 20 outfalls per stream mile indicates high IDP. |
| 5. Age of Subwatershed Development | Defined as the average age of the majority of development in a subwatershed. High IDP is often indicated for developments older than 50 years. Determined from tax maps and parcel data, or from other known information about neighborhoods. |
| 6. Sewer Conversion | Subwatersheds that had septic systems but have been connected to the sanitary sewer system in the last 30 years have high IDP. |
| 7. Historic Combined Sewer Systems | Subwatersheds that were once served by combined sewer system but were subsequently separated have a high IDP. |
| 8. Presence of Older Industrial Operations | Subwatersheds with more than 5% of its area in industrial sites that are more than 40 years old are considered to have high IDP. Determined from historic zoning, tax maps, and "old-timers." |
| 9. Aging or Failing Sewer Infrastructure | Defined as the age and condition of the subwatershed sewer network. High IDP is indicated when the sewer age exceeds design life of its construction materials (e.g., 50 years) or when clusters of pipe breaks, spills, overflows or I/I are reported by sewer authorities. |
| 10. Density of Aging Septic Systems | Subwatersheds with a density of more than 100 older drain fields per square mile are considered to have high IDP. Determined from analysis of lot size outside of sewer service boundaries. |

1. Past Discharge Complaints and Reports

Many communities already have some handle on where illicit discharges have occurred in the past, based on past complaints, reports and interviews with spill responders and public works repair crews. Pollution complaints made to the local environmental or health department are also worth analyzing. Each of these historical sources should be analyzed to determine if any patterns or clusters where illicit discharges have historically occurred can be found. Ideally, the number of past discharge complaints should be expressed on a subwatershed basis. Even if there is not enough data to quantify past discharges, it may be helpful to get a qualitative opinion from public works crews.

2. Poor Dry Weather Water Quality

If dry weather water quality monitoring data have been collected for local streams, it can be an extremely useful resource to screen subwatersheds for IDP. In particular, look for extreme concentrations of enterococci or *E. coli*, or high ammonia-nitrogen or conductivity. Remember to edit out any samples that were collected during or shortly after storm events, as they reflect the washoff of pollutants during storm water runoff. In general, most communities have more subwatersheds than baseflow monitoring stations, so complete coverage is usually lacking. The following benchmarks are recommended to flag streams with high IDP, based on individual samples of dry weather water quality that exceed:

- Fecal coliform or *E. coli* standards (e.g., typically 1,000 to 5,000 MPN/100 ml)
- Ammonia-nitrogen levels of 0.30 mg/l
- Total phosphorus of 0.40 mg/l
- Conductivity levels that exceed the 90th percentile value for the pooled dataset.

Subwatersheds can be classified as having a moderate risk if stream water quality values exceed half the benchmark value. An alternative approach is to statistically analyze long-term dry weather water quality monitoring dataset to define breakpoints (e.g., 50th, 75th, and 90th percentiles).

3. Density of Generating Sites or Industrial NPDES Storm Water Permits

The density of potential generating sites in a subwatershed can be a good screening factor, if land use and business databases are available. The basic database screening method used to locate commercial, industrial, institutional, municipal and transport-related generating sites is described in Chapter 1 and Appendix A. From the standpoint of discharge screening, the key variable to derive is the density of potential generating sites (e.g., sites/square mile). As a rule of thumb, more than 10 potential generating sites per square mile would indicate a high IDP, while subwatersheds with three to 10 generating sites per square mile might suggest a medium IDP.

Alternatively, communities may want to develop screening factors based on the density of industrial storm water permits in place within the subwatershed. State or federal regulatory agencies often have geospatial databases of industrial NPDES discharges that can be rapidly screened. Pretreatment programs are another valuable source of information on industrial and non-domestic discharges to the sanitary system.

4. Storm Water Outfall Density

The density of outfalls in a subwatershed is an effective discharge screening factor, and is expressed in terms of the number of outfalls per stream mile. Outfall density can be determined by analyzing storm drain maps, if they exist (although they often miss the smaller diameter outfalls that can also produce discharges). In general, subwatersheds that have more than 20 mapped outfalls per stream mile may indicate a higher risk for IDP. Alternatively, the breakpoints for outfall density can be statistically analyzed based on the frequency across all subwatersheds.

5. Age of Subwatershed Development

The average age of development in a subwatershed may predict the potential for illicit discharge problems. For example, a subwatershed where the average age of development is more than 100 years was probably constructed before sewer service was widely available, and many of the pipes and connections may have changed over the years as a result of modernization and redevelopment. Presumably, the risk of potential discharges would be higher in these older subwatersheds. By contrast, a recently developed subwatershed may have a lower discharge risk due to improved construction materials, codes and inspections. Therefore, high IDP may be indicated when subwatershed development is more than 50 years old, with medium IDP for 20 to 50 year old development, and low IDP if fewer than 20 years old. You should always check with local building and plumbing inspectors to confirm the building eras used in the screening analysis. The actual age of development can be estimated by checking tax maps and plats, or based on architecture, or common knowledge of neighborhoods.

6. Sewer Conversion

Subwatersheds that were once served by septic systems but were subsequently connected often have a high IDP. These subwatersheds are identified by reviewing past sewer construction projects to determine when and why sewer service was extended.

7. Historic Combined Sewer Systems

Subwatersheds that were once served by combined sewer systems but were subsequently separated often have a high IDP. They can be identified by reviewing past municipal separation projects.

8. Presence of Older Industrial Operations

Older industrial areas tend to have a high potential for illicit cross-connections for several reasons. First, sanitary sewers may not have been installed to handle wash water, process water and other discharge flows when the operation was originally constructed. In the past, storm drains were often used to handle non-sewage discharges at older industrial facilities. In addition, sanitary and storm drain lines built in different eras are poorly mapped, which increases the chance that someone gets the plumbing wrong during an expansion or change in operations at the facility. As a result, older industries may inadvertently discharge to floor drains or other storm drain connections thinking they are discharging pretreated water to the sanitary sewer. Finally, older industries that produce large volumes of process water may not have enough sanitary sewer capacity to handle the entire discharge stream, causing them to improperly discharge excess water through the storm drain system.

For these reasons, subwatersheds where older industry is present should be regarded as having a high IDP. For operational purposes, older industry is defined as sites that predate the Clean Water Act (e.g., 40 years old or more). They can be identified from historic zoning and land use maps, old parcel records or talking with old-timers.

9. Aging or Failing Sewer Infrastructure

Aging or failing sewer infrastructure often signals potential illicit discharges, and can be defined by the age and condition of the subwatershed sewer network. High IDP is indicated when the sewer age exceeds the design life of its construction materials (e.g., 50 years) or when clusters of pipe breaks, spills, overflows or infiltration and inflow (I&I) are reported by sewer authorities. Older and aging sewer infrastructure experience more leaks, cross-connections and broken pipes that can contribute sewage to the storm drain system. The key factor to determine is the approximate age of the sewer pipes and their construction materials, which can be gleaned from sewer maps I&I studies, or interviews with crews that regularly repair broken or leaking sewer pipes.

10. Density of Aging Septic Systems

Subwatersheds located outside of the sewer service area are presumably served by septic systems. Septic systems more than 30 years old are prone to failure, based on many site factors (Swann, 2001). In general, a high IDP is indicated if older septic tank density exceeds 100 per square mile. Sewer envelope boundaries or sewer network maps can be helpful to identify subwatersheds that are served by septic systems. Actual density is determined by counting or estimating the total number of septic households in the subwatershed. Tank density should be expressed as septic system units per square mile (average lot size can also be used as a surrogate estimator).

### *Step 4: Screen for Illicit Discharge Potential at the Subwatershed and Community Level*

The process for screening IDP at the subwatershed level is fairly simple. The first step is to select the group of screening factors that apply most to your community, and assign them a relative weight. Next, points are assigned for each subwatershed based on defined scoring criteria for each screening factor. The total subwatershed score for all of the screening factors is then used to designate whether it has a low, medium or high risk to produce illicit discharges. Table 15 provides an example. Based on this comparison, high-risk subwatersheds are targeted for priority field screening. It is important for program managers to track and understand which screening factors contributed to identifying a watershed as "high-risk," as this may affect the type of investigatory strategy that is used for a particular watershed.

**Table 15: Prioritizing Subwatersheds Using IDP Screening Factors**

| | **Past Discharge Complaints/ Reports** (total number logged) | **Poor dry weather water quality** (% of times bacteria standards are exceeded) | **Density of storm water outfalls** (# of outfalls per stream mile) | **Average age of development** (years) | **Raw IDP score** | **Normalized IDP score**** |
|---|---|---|---|---|---|---|
| Subwatershed A | 8 (2)* | 30% (2)* | 14 (2)* | 40 (2)* | 8 | 2 |
| Subwatershed B | 3 (1) | 15% (1) | 10 (2) | 10 (1) | 5 | 1.25 |
| Subwatershed C | 13 (3) | 60% (3) | 16 (2) | 75 (3) | 11 | 2.75 |
| Subwatershed D | 1 (1) | 25% (1) | 9 (1) | 15 (2) | 5 | 1.25 |
| Subwatershed E | 5 (1) | 15% (1) | 21 (3) | 20 (1) | 6 | 1.5 |

*Notes:*
* The number in parentheses is the IDP "score" (with 3 having a high IDP) earned for that subwatershed and screening factor. Basis for assigning scores (based on benchmarks) to assess IDP is as follows:
Past discharge complaints/reports: <5 = 1; 5-10 = 2; >10 = 3
Dry weather water quality: <25% = 1; 25-50% = 2; >50% = 3
Storm water outfall density: <10 = 1; 10-20 = 2; >20 = 3
Average age of development: <25 = 1; 25- 50 = 2; >50 = 3

** Normalizing the raw IDP scores (by dividing the raw score by the number of screening factors assessed) will produce scores that fall into the standard scale of 1 to 3 for low to high IDP, respectively.

The example provided in Table 15 uses four screening factors to assess five subwatersheds in a community. Data for each factor are compared against assigned benchmarks, as shown in the table. Each subwatershed receives a specific score for each individual screening factor. These scores are then totalled for each subwatershed, and the one with the highest score is given top priority screening. In this case, the screening priority would be given to Subwatershed C, then A, followed by E. Subwatersheds B and D, with the lowest potential for illicit discharges, have the lowest priority.

A similar screening process can be used to evaluate the IDP for the community as a whole. In this case, the entire population of subwatersheds in the community is analyzed to collectively determine the frequency of the three risk areas: high, medium, and low. Predefined criteria for classifying the community's IDP should be developed.

Table 16 and Figure 9 present an example system for classifying IDP as minimal, clustered or severe, based on the proportion of subwatersheds in each risk category. The community-wide assessment helps program managers define their initial IDDE program goals and implementation strategies, and target priority subwatersheds for field investigations.

### *Step 5: Generate Maps to Support Field Investigations*

The last step in this program component involves generating the maps that field crews need to screen outfalls in priority subwatersheds. More detail on mapping requirements is provided in Chapter 11. The basic idea is to create relatively simple maps that show streams, channels, streets, landmarks, property boundaries and known outfall locations. The idea is to provide enough information so crews can find their way in the field without getting lost, but otherwise keep them uncluttered. Low altitude aerial photos are also a handy resource when available.

**Table 16: Community-wide Rating of Illicit Discharge Potential**

| Rating | Indicators |
|---|---|
| Minimal (no known problems) | Majority of subwatersheds have a Low IDP risk, with the remainder having Medium IDP risk |
| Clustered (isolated problems) | More than 20% of subwatersheds with a Medium or High IDP risk that are in close proximity to each other |
| Severe (severe problems) | More than 50% of subwatersheds with a Medium or High IDP risk or more than 20% of subwatersheds with a High IDP risk |

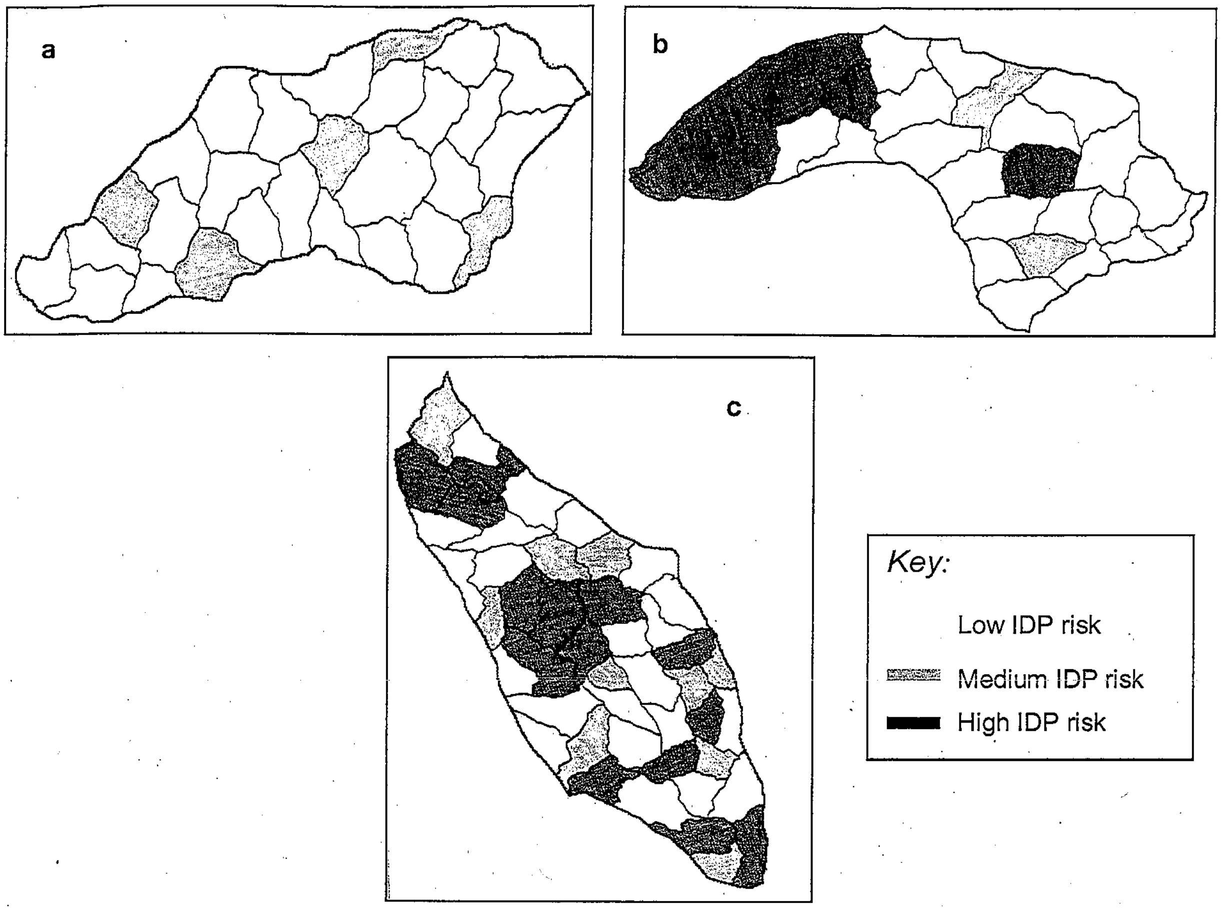



**Figure 9: Communities with Minimal (a), Clustered (b), and Severe (c) Illicit Discharge Problems**

# Chapter 6: Developing Program Goals and Implementation Strategies

*Purpose:* This program component defines the goals and performance milestones to measure progress in IDDE program implementation during the first permit cycle, and selects the most appropriate and cost-effective strategies to find, fix and prevent illicit discharges. The goals and strategies ensure that scarce local resources are allocated to address the most severe illicit discharge problems that cause the greatest water quality problems in the community.

*Method*: The basic method is to analyze the results of the IDDE audit, desktop analysis and local water quality conditions to develop realistic, achievable and measurable goals for the program. The public and other stakeholders should be involved in the goal setting process. Once goals are selected, program managers need to select the appropriate implementation strategies and develop a timeline to make them happen. Both goals and strategies should closely align with the type and severity of water quality problems and local watershed management priorities. The probable contribution of illicit discharges to specific water quality problems should be estimated or modeled to determine the degree to which control efforts can meet local TMDLs, bacteria standards for water contact recreation, or other local water quality concerns.

*Desired Product or Outcome(s)*: Agreement on program goals, measurable indicators and implementation strategies that address four key areas:

- Overall program administration
- Outfall assessment
- Finding and fixing illicit discharges
- Prevention of illicit discharges

*Budget and/or Staff Resources Required:* Staff effort to draft the goals and strategies, conduct needed meetings, respond to comments and finalize ranges from two to six weeks. Goals and strategies should be revisited and updated annually and at the end of each permit cycle. Staff and budget costs are not anticipated to be high unless a fundamental shift in program goals occurs.

*Integration with Other Programs*: Goal setting is always a good opportunity for public involvement, storm water education and watershed outreach. Effective implementation strategies often involve cost sharing with other departments and even other communities for monitoring equipment and lab facilities, hotlines, and education (e.g., public health/septic system programs).

## 6.1 Overview of Goals and Strategies Development

Communities can define program goals and implementation strategies once they understand the extent of their illicit discharge problem and how it influences local water quality. Initial program goals should be realistic and provide specific completion milestones to measure program compliance. Measurable goals enable a community to track and evaluate permit compliance over time, and to reassess and modify the program over time. The most basic measure of program effectiveness is to assess whether program goals are being met. So, if a program goal is to walk all stream miles and inventory all outfalls in the MS4 within the first permit cycle, this becomes a benchmark that determines program effectiveness. If a community finds that they only managed to walk and inventory 80% of stream miles, the program may need to be modified so that a full screening sweep is completed in a permit cycle, or they may need to adjust the goal or benchmark.

## 6.2 Develop Initial Program Goals

The NPDES Phase II MS4 permit regulations grant communities considerable flexibility to develop program goals, as long as they are defined in a measurable way to gauge permit compliance and program effectiveness. EPA (2000e) states that goals "should reflect the needs and characteristics of the operator and the area served by its small MS4. Furthermore, they should be chosen using an integrated approach that fully addresses the requirements and intent of the minimum control measure."

With this in mind, a series of representative goals that might be set for an IDDE program are presented in Table 17, along with proposed milestones. Four broad types of goals should be developed for every program:

1. Overall program administration
2. Outfall assessment
3. Preventing illicit discharges
4. Finding and fixing illicit discharge

The assumed timeframe is based on a five-year permit cycle. Some of the program goals outlined in Table 17 are considered essential while others are optional or recommended. Communities should feel free to adapt these suggested program goals to reflect their unique conditions and capabilities, or create new ones. The key point is that program goals should always have a timeframe to serve as a benchmark for whether the goal has been achieved.

Implementation strategies are designed to achieve program goals, and vary depending on the types and severity of illicit discharge problems in the community. These are outlined in more detail in the next section.

| Table 17: Measurable Goals for an IDDE Program | | |
|---|---|---|
| **EXAMPLE MEASURABLE GOALS** | **TIMEFRAME** | **PRIORITY** |
| **Goals related to overall program administration** | | |
| Audit existing capabilities and identify needs | Immediately | ● |
| Designate one program head and identify key support staff | | ● |
| Develop a complete list of ongoing activities related to IDDE | | ○ |
| Coordinate and communicate with other affected agencies | At program start up and continuously and regularly after that | ● |
| Develop a projected 5-year budget | | ● |
| Secure funding to match 5-year goals | | ● |
| Draft and promulgate new or modified ordinance | Year 1 | ● |
| Establish a tracking and reporting system | Year 1 | ● |
| **Goals related to outfall assessment** | | |
| Define and characterize drainage areas or sewer sheds | Year 1 | ● |
| Walk all stream miles | Begin in Year 1 and complete first screening by end of permit cycle. Repeat once per permit cycle | ● |
| Develop a digital (e.g., GIS) map of all outfalls, land use, and other relevant infrastructure | Year 1 and continuously and regularly after that | ● |
| Secure analytical laboratory services either internally or by arrangement with a private laboratory | Initiate in conjunction with field screening | ● |
| Sample and trace the source of a percentage of flowing outfalls each year of permit cycle | Initiate during first permit cycle and expand and enhance where problems are observed | ● |
| Conduct regular in-stream assessments | | ○ |
| Conduct investigations at a percentage of non-flowing outfalls with poor in-stream water quality to look for intermittent flows | | ○ |
| Integrate all collected stream data and citizen complaints into the GIS system | Initiate during first year and expand and enhance with time | ○ |
| **Goals related to preventing illicit discharges** | | |
| Distribute educational materials to citizens and industries | Initiate during first year and expand and enhance with time | ○ |
| Conduct storm drain stenciling | Initiate during first permit cycle and expand and enhance where problems are observed | ○ |
| Hold hazardous waste collection days at least annually | | ○ |
| Conduct upland subwatershed site reconnaissance surveys to better characterize generating site potential | | ○ |
| **Goals related to finding and fixing illicit discharges** | | |
| Develop a spill response plan and coordinate emergency response with other agencies | Immediately | ● |
| Remove all obvious illicit discharges | Ongoing in conjunction with field screening and in response to hotline reports | ● |

| Table 17: Measurable Goals for an IDDE Program | | |
|---|---|---|
| EXAMPLE MEASURABLE GOALS | TIMEFRAME | PRIORITY |
| Train staff on techniques to find the source of an illicit discharge | Initiate during first year and expand and enhance with time | ● |
| Repair a fraction of the illicit discharges identified through field screening or citizen complaints | Initiate during first permit cycle and expand and enhance where problems are observed | ● |
| Establish a hotline for public to call in and report incidents (consider establishing performance standards, such as guaranteed response time) | Initiate during first year and expand and enhance with time | ❍ |
| Inspect and dye-test all industrial facilities | Initiate during first permit cycle and expand and enhance where problems are observed | ❍ |
| Develop a system to track results of on-site inspections | Initiate during first year and expand and enhance with time | ❍ |
| Establish an Adopt-a-Stream program | Initiate during first permit cycle and expand and enhance where problems are observed | ❍ |
| Establish pre-approved list of plumbers and contractors to make corrections | Initiate during first year and expand and enhance with time | ❍ |
| *Key:* ● Essential ❍ Optional but Recommended | | |

Ultimately, IDDE program goals should be linked to water quality goals. Some common examples of water quality goals include:

- Keep raw or poorly-treated sewage out of streams
- Reduce pollutant loads during dry weather to help meet the TMDL for a water body
- Meet bacteria water quality standards for contact recreation during dry weather flows
- Reduce toxicant and other pollutant discharges to a stream to restore the abundance and diversity of aquatic insects or fish

A well-designed IDDE program may not guarantee that water quality goals will be always be achieved. Indeed, if program managers can document that illicit discharges do not contribute to poor water quality, they may want to shift resources to other pollution sources or practices that do. Burton and Pitt (2002) offer a complete discussion on designing and conducting a receiving water investigation.

## 6.3 Crafting Implementation Strategies

In order to meet program goals, managers must devise cost-effective implementation strategies that are most appropriate for the types of illicit discharge problems they actually have. The community-wide illicit discharge potential (IDP) developed during the desktop analysis can be quite helpful in choosing implementation strategies. Table 18 presents implementation strategies that are geared to the findings of the community-wide IDP. As the community acquires more program experience, they can refine the strategies to better address program goals or unique watershed conditions (Table 19).

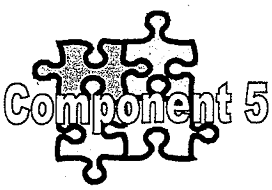
Perhaps the most important implementation strategy is targeting—screening, education and enforcement efforts should always be focused on subwatersheds, catchments or generating sites with the greatest IDP.

Adaptability after program startup is also an important strategy. Strategies developed from the desktop analysis should be constantly adjusted to reflect knowledge gained from field screening, hotline reports and other monitoring information.

**Table 18: Linking Implementation Strategies to Community–wide IDP**

| Type | Examples of Implementation Strategy |
|---|---|
| **Minimal IDP** | • Conduct field screening of outfalls in the context of broader watershed assessment and restoration initiatives using the Unified Stream Assessment (CWP, 2004) or a comparable physical stream assessment approach that has broader focus and benefits.<br>• Integrate IDDE program efforts into more comprehensive watershed assessment and restoration efforts where multiple objectives are being pursued (e.g., storm water education).<br>• Target and coordinate with existing small watershed organizations as partners to accomplish inventory and data collection efforts.<br>• Establish hotline to report suspicious discharges. |
| **Clustered IDP** | • Conduct limited sampling in the suspect areas. The most cost-effective approach will likely involve using outside laboratory services to avoid capital costs for special equipment (in some cases a municipal laboratory may be available for limited cost).<br>• Select a small set of indicator parameters using the nature of historic problems and land use as a guide.<br>• Target education program in problem areas.<br>• Look for partnerships with local watershed groups to regularly monitor problem areas.<br>• Establish a hotline to report suspicious discharges. |
| **Severe IDP** | • Establish a hotline to report suspicious discharges.<br>• Conduct and repeat screening in all subwatersheds<br>• Plan for more rigorous sampling approach to make establishment of internal laboratory set up more cost effective (i.e., plan for equipment expenditures for sample collection and analysis). Considerations include: expanding set of parameters to use as indicators, adopting a strategy for targeting intermittent discharges, and establishing in-stream stations to supplement screening effort.<br>• Develop a community-specific chemical "fingerprint" of various flow sources to facilitate differentiation between likely flow sources.<br>• Develop community-wide educational messages aimed at increasing public awareness and targeted education programs tailored to problem areas.<br>• Look for partnerships with local watershed groups to be regular monitors of problem areas through an adopt-a-stream approach.<br>• Emphasize cross-training of municipal employees to develop a broader reach of program efforts and lead by example by ensuring municipal facilities are not contributing to illicit discharge problem. |

| Table 19: Customizing Strategies for Unique Subwatershed Screening Factors | | |
|---|---|---|
| **Initial Problem Assessment** | **Screening Factor** (from Table 14) | **Example Implementation Strategies** |
| **Aging Sewer Infrastructure and/or Converted Combined System** | • Complaints of sewage discharges<br>• Poor dry weather quality<br>• High outfall density<br>• Septic to sewer conversion<br>• Historic combined system<br>• Aging sewers | • Institute a point of sale inspection and verification process.<br>• Select a small set of indicator parameters that focuses on sewage connections.<br>• Develop cost share program to assist property owners with connection correction. |
| **Aging Septic Infrastructure and/or Converted Combined System** | • Aging septic systems | • Develop targeted education program for septic system maintenance and institute a point of sale inspection and verification process.<br>• Develop cost share capabilities to assist property owners with upgrade of system. |
| **Discharges from Generating Sites** | • Density of generating sites<br>• Older industry<br>• Past complaints and reports | • Link IDDE program to existing industrial NPDES discharge permits, and inspect storm water management pollution prevention plans.<br>• Develop targeted training and technical assistance programs tailored to specific generating sites.<br>• Aggressively enforce fines and other measures on chronic violators. |
| **High Spill or Dumping Potential** | • Past complaints and reports | • Establish a hotline and develop community-wide educational messages aimed at increasing public awareness.<br>• Look for partnerships with local watershed groups to regularly monitor or adopt problem sites.<br>• Increase number and frequency of used oil and hazardous waste recycling stations.<br>• Post signs, with hotline reporting number at dumping sites. |




# Chapter 7: Searching for Illicit Discharge Problems in the Field

*Purpose:* This program component consists of detective work, and involves rapid field screening of outfalls in priority subwatersheds followed by indicator monitoring at suspect outfalls to characterize flow types and trace sources.

*Method(s):* The primary field screening tool is the Outfall Reconnaissance Inventory (ORI), which is used to find illicit discharge problems and develop a systematic outfall inventory and map of the MS4. The ORI is frequently supplemented with more intensive indicator monitoring methods to test suspect outfalls. A wide range of monitoring methods can be used; this chapter describes a framework for choosing the safest, most accurate and repeatable methods for a community.

*Desired Product or Outcome(s):* The search for illicit discharge problems yields several important management products, including:

- An updated map of the locations of all outfalls within the MS4
- Incorporation of ORI data into the outfall inventory/tracking system
- Design and implementation of an indicator monitoring strategy to test suspect outfalls
- Creation of a local chemical "fingerprint" library of pollutant concentrations for various discharge flow types
- Data reports that evaluate the significance and distribution of illicit discharge problems in the community

*Budget and/or Staff Resources Required:* Field screening and indicator monitoring can consume substantial staff and budget resources. Monitoring costs are closely related to the number of outfalls screened and the complexity of illicit discharge problems discovered. An MS4 that screens 10 stream miles and analyzes 80 indicator samples each year can expect to spend about $15,000 to $35,000. Consequently, choosing which indicator(s) to use in a community (and when and where to use them) ranks as one of the most important budget decisions for any project manager.

*Integration with Other Programs:* Program managers should explore two strategies to integrate field screening and indicator monitoring with other programs to achieve cost savings. The first strategy links outfall screening to broader stream corridor assessments that support local watershed restoration efforts. Often, watershed organizations and "stream waders" can be enlisted and trained to conduct outfall screening. The second strategy is to find a local agency partner to conduct laboratory analysis (such as a drinking water or wastewater treatment plant).

## 7.1 Overview of Searching for Illicit Discharge Problems in the Field

This chapter provides basic information about the field and laboratory strategies needed to detect illicit discharges, beginning with a field screening technique designed to gather basic information and identify highly suspect outfalls or obvious discharges. Next, it provides a basic framework for using the data from this screening to address obvious discharges, develop a chemical monitoring program, and make future program decisions. Finally, it summarizes the basic options for conducting an ongoing chemical monitoring program. The approaches outlined here are only summarized briefly, and primarily in the context of overall program management. Much more detailed and "hands-on" information is provided in Chapters 11 and 12 that provide specific methods and technical guidance for field crew and laboratory staff.

## 7.2 The Outfall Reconnaissance Inventory (ORI)

The field screening technique recommended for an IDDE program is the Outfall Reconnaissance Inventory or ORI. The ORI is a stream walk designed to inventory and measure storm drain outfalls, and find and correct continuous and intermittent discharges without in-depth laboratory analysis (Figure 10). The ORI should be completed for every stream mile or open channel within the community during the first permit cycle, starting with priority subwatersheds identified in the desktop analysis. Outfall screening requires relatively little expertise, and can be incorporated into other stream assessments such as the Unified Stream Assessment (Kitchell and Schueler, 2004).

The ORI can discover obvious discharges that are indicated by flowing outfalls with very high turbidity, strong odors and colors, or an "off the chart" value on a simple field test strip. When obvious discharges are found, field crews should immediately track down and remove the source (see Chapters 8 and 13). In other instances, ORI crews may encounter a transitory discharge, such as a liquid or oil spill that should be immediately referred to the appropriate agency for cleanup (Figure 11).

**Figure 10: Measuring an outfall as part of the ORI**

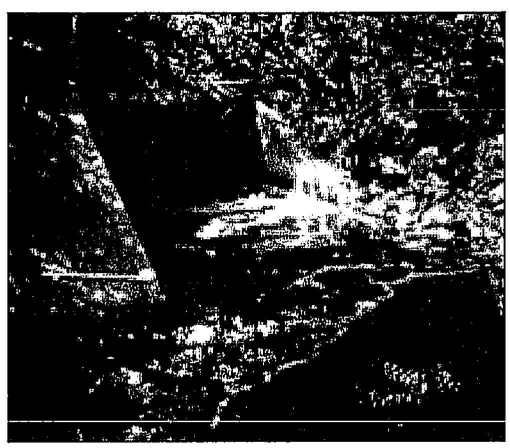


**Figure 11: Some discharges are immediately obvious**

The ORI is not meant to be a "one size fits all" method, and should be adapted to suit the unique needs of each community. Program managers should also modify the ORI over time to reflect field observations, crew experience, new or modified indicators, and any other innovations that make fieldwork easier or faster. Table 20 summarizes the four basic steps to conduct an ORI, and more detail on ORI protocols is provided in Chapter 11.

## 7.3 Interpreting ORI Data

Once the first few ORI surveys are conducted, data can be analyzed to confirm and update the desktop analysis originally used for targeting subwatersheds. The ORI data analysis follows four basic steps, which are described in Table 21. Ideally, ORI data should be stored within a continuously-updated geospatial tracking system.

**Table 20: Field Screening for an IDDE Program**

| Step | Strategies |
|---|---|
| Step 1. Acquire necessary mapping, equipment and staff | • Use basic street maps or detailed maps from initial assessment<br>• Minimal field equipment required; use a portable spectrophotometer if desired<br>• Two staff per crew with basic field training required; more specialized staff or training is optional |
| Step 2. Determine when to conduct field screening | • During dry season and leaf off conditions<br>• After a dry period of at least 48 hours<br>• Low groundwater levels |
| Step 3. Identify where to conduct field screening (based on desktop assessment) | • Minimal: integrate field screening with broader watershed or stream assessments<br>• Clustered: screen drainage areas ranking High and Medium first for illicit discharge potential<br>• Severe: screen all outfalls systematically |
| Step 4. Conduct field screening | • Mark and photograph all outfalls<br>• Record outfall characteristics<br>• Simple monitoring at flowing outfalls<br>• Take flow sample at outfalls with likely problems<br>• Deal with major problems immediately |

| Table 21: Field Data Analysis for an IDDE Program | |
|---|---|
| **Step** | **Considerations** |
| Step 1. Compile data from the ORI | • Compile GPS data and photographs of outfall locations<br>• Enter ORI data into database<br>• Send any samples for lab analysis |
| Step 2. Develop ORI designation for outfalls | • Use ORI data to designate outfalls as having obvious, suspect, potential, or unlikely discharge potential |
| Step 3. Characterize the extent of illicit discharge problems | • Use data from initial assessment<br>• Use outfall designation data<br>• Update initial assessment of illicit discharge problems as minimal, clustered, severe |
| Step 4. Develop a monitoring strategy | • At a minimum, sample 10% of flowing outfalls per year<br>• Repeat field screening in second permit cycle<br>• Use various monitoring methods depending on outfall designation and subwatershed characteristics |

## 7.4 Design and Implementation of an Indicator Monitoring Strategy

The next step is to design an indicator monitoring program to test suspect or problem outfalls to confirm whether they are actually an illicit discharge, and determine the type of flow. From a program management standpoint, six core issues need to be considered during the design of the monitoring strategy, as shown in Table 22.

The indicator monitoring strategy should be concentrated primarily on continuous and intermittent discharges, and can be adapted to isolate the specific flow type found in a discharge. Figure 12 presents an overall monitoring design framework that organizes some of the key indicators and monitoring techniques that may be needed. In general, different indicators and monitoring methods are used depending on whether flow is present at an outfall or not. The details of the discharge monitoring framework are described in Chapter 12. The basic framework should be adapted to reflect the unique discharge problems and analytical capabilities of individual communities.

Some of the recommended monitoring strategies are discussed below. The preferred method to test flowing outfalls is the **flow chart method** that uses a small set of indicator parameters to determine whether a discharge is clean or dirty, and predicts its or flow type (Pitt, 2004). The flow chart method is particularly suited to distinguish sewage and washwater flow types. Industrial sites may require special testing, and the **benchmark concentrations method** includes several supplemental indicators to distinguish industrial sources.

| Table 22: Indicator Monitoring Considerations |
|---|
| • Use ORI data to prioritize problem outfalls or drainage areas<br>• Select the type of indicators needed for your discharge problems<br>• Decide whether to use in-house or contract lab analytical services<br>• Consider the techniques to detect intermittent discharges<br>• Develop a chemical library of concentrations for various flow types<br>• Estimate staff time, and costs for equipment and disposable supplies |

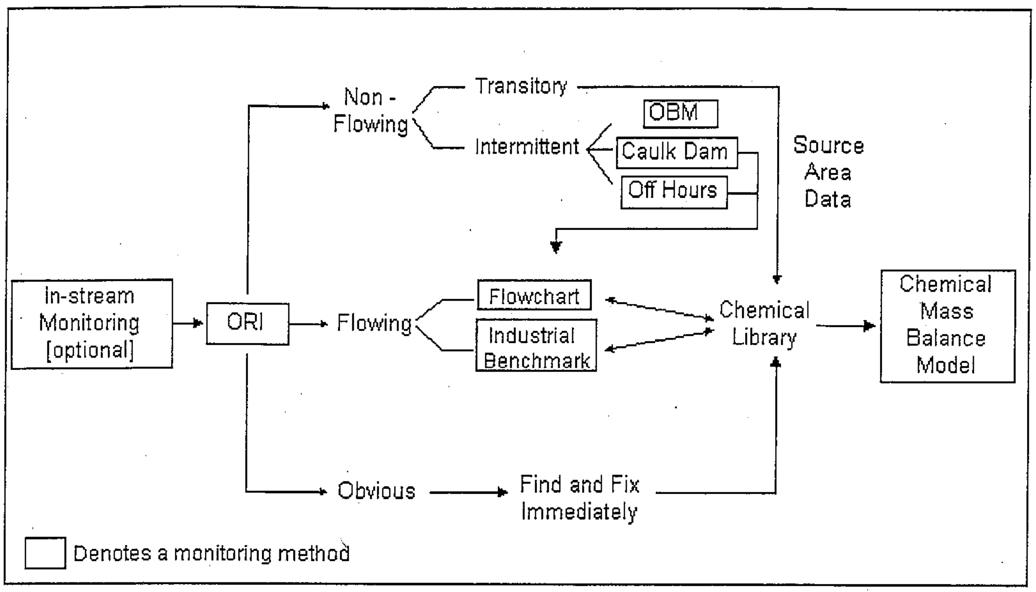



**Figure 12: IDDE Monitoring Framework**

Non-flowing outfalls are more challenging to diagnose. Intermittent flows can be diagnosed using specialized monitoring techniques such as:

- Off hours monitoring
- Caulk dams
- Optical brightener monitoring traps

When intermittent discharges are captured by these specialized techniques, samples are normally diagnosed using the flow chart method.

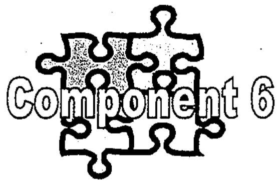
Transitory discharges are extremely difficult to detect with routine indicator monitoring, and are frequently identified from hotline reports. Transitory discharges are usually diagnosed by inspection, although water quality samples may be collected to support enforcement measures.

As communities acquire more monitoring data, they should consider creating a **chemical "fingerprint" library**, which is a database of the chemical make-up of the many different flow types in the community. Chemical libraries should include sewage, septage, washwater, and common industrial flows. Default values for the chemical library can initially be established based on existing research and literature values. Data are then updated based on local monitoring to develop more accurate decision points in the flow chart or benchmark methods. Clean water sources such as tap water, groundwater, spring water, and irrigation water are also important entries in the chemical library. The chemical library should also characterize the water quality of known or unknown transitory discharges sampled in the field. Over time, chemical library data should help a community better understand the potential pollutant loads delivered to receiving waters from various generating activities.

These library data can be used to support more advanced strategies such as the **Chemical Mass Balance Model** (CMBM) method. This method, developed by the University of Alabama as part of this project (Karri, 2004), is particularly useful in identifying flow types in blended discharges, where groundwater or tap water is diluted or commingled with sewage and other illicit discharges. The CMBM requires substantial upfront work to develop an accurate chemical library for local flow types. Specifically, the library requires 10-12 samples for each flow type (for industrial flow types, samples can be obtained in association with NPDES pre-treatment programs). A user's guide for the CMBM can be found in Appendix I.

## Section 7.5 Field and Lab Safety Considerations

Program managers should take into account and fully plan for all necessary field and laboratory safety precautions. Most communities already have well established standard operating procedures they follow when conducting field and lab work, and these typically provide an excellent starting point for IDDE programs. Chapters 11, 12, and 13 along with Appendices F and G provide guidance on specific considerations associated with IDDE programs. Of particular note is that program managers may want to consider requiring/ recommending field crews be vaccinated against Hepatitis B, particularly if the crews will be accessing waters known to be contaminated with illicit sewage discharges. Program managers should contact local health department officials to explore this issue in more detail prior to making a decision.




# Chapter 8: Isolating and Fixing Individual Illicit Discharges

*Purpose:* This program component uses a variety of tools to trace illicit discharge problems back up the pipe to isolate the specific source or improper connection that generates the discharge. This often requires improved local capacity to locate specific discharges, make needed corrections and maintain an enforcement program to ensure repairs.

*Method(s):* Five basic tools exist to isolate and fix individual discharges, including:

- Pollution reporting hotline
- Drainage area investigations
- Trunk investigations
- On-site discharge investigations
- Correction and enforcement

*Desired Product or Outcome(s):* Finding and fixing illicit discharges is the core goal of any IDDE program. The process of finding and fixing discharges has several desirable outcomes, such as:

- Improved water quality
- Increased homeowner and business awareness about pollution prevention
- Maintenance of a tracking system to document repairs and identify repeat offenders.

*Budget and/or Staff Resources Required*: Budget and staff resources needed to find illicit discharges vary greatly. Some discharge sources will be immediately obvious, while others will require extensive investigations up the pipe until the source can be sufficiently narrowed. Fixing the problem once it is identified is more predictable and can often involve qualified contractors. Costs associated with repairs can also be fully incurred by the offending party or shared, depending on the nature and extent of the illicit discharge.

*Integration with Other Programs*: Two important aspects of this program component can be integrated with other NPDES minimum management measures and storm water permitting. First, the pollution hotline can be an important element of any local storm water education initiative. Second, on-site illicit discharge investigations should be closely coordinated with industrial NPDES storm water site inspections.

## 8.1 Overview of Isolating and Fixing Individual Illicit Discharges

The ultimate goal of every IDDE program is to find and fix illicit discharges, and a range of tools are available to meet this objective. The ensuing chapter discusses each of the tools in more detail. The choice of which tools are used depends on the nature of the local storm drain system, and the type and mode of entry of the discharges.

## 8.2 Isolating Illicit Discharges

Outfall screening and monitoring are excellent for finding illicit discharge problems, but they often cannot detect most intermittent or transient flows, nor can they always isolate the exact source, particularly when the outfall has a large contributing area and an extensive pipe network. This section provides guidance on four tools to find individual illicit discharges. The first tool is a pollution complaint hotline, which is particularly effective at finding obvious illicit discharges, such as transitory flows from generating sites and sewer overflows. Citizens provide free surveillance around the clock, and their reports should prompt rapid investigations and enforcement. The other three investigative tools involve drainage area, trunk, and on-site investigations.

### *Pollution Complaint Hotline*

A complaint hotline is a dedicated phone number or website where citizens can easily report illicit discharge and pollution concerns. The hotline should always be supported by prompt investigations of each complaint by trained inspectors, usually within 24 hours. Many Phase I communities have utilized hotlines to track down intermittent and transitory discharges, and regard them as one of their most effective tools to isolate illicit discharges (CWP, 2002). Some of the benefits and challenges Phase I communities have encountered in administering an IDDE complaint hotline in summarized in Table 23.

Six basic steps are needed to establish and maintain a successful IDDE complaint hotline, which are outlined in Table 24. More detailed guidance on establishing a hotline is provided in Appendix C, along with a sample illicit discharge incident tracking form.

It is important to keep in mind that a successful hotline requires considerable advertising and outreach to keep the phone number fresh in the public's mind. Also, program managers should continuously monitor response times, inspection outcomes, and any enforcement taken. All complaints should be entered into the IDDE tracking system so that complaints can be analyzed.

**Table 23: Benefits and Challenges of a Complaint Hotline**

| Benefits | Challenges |
|---|---|
| • Leads to early detection and correction of illicit discharges<br>• Encourages active public stewardship<br>• Can "piggyback" on other call response needs<br>• Identifies suspected facilities for further investigation and education<br>• Increases facilities' and municipalities' sense of accountability<br>• Increases likelihood of discovering intermittent discharges | • Time and money to provide 24/7 service<br>• Marketing the hotline number<br>• Establishing inter- and intra-departmental process |

| Table 24: Steps to Creating and Maintaining Successful IDDE Hotline | |
|---|---|
| **Steps** | **Key Elements** |
| 1. Define the scope | • Determine if a hotline is needed<br>• Define the intent of the hotline<br>• Define the extent of the hotline |
| 2. Create a tracking and reporting system | • Design reporting method<br>• Design response method |
| 3. Train personnel | • The basics and importance of IDDE<br>• The complaint hotline reporting, investigation and tracking process<br>• How to provide good customer service<br>• Expected responsibilities of each department/agency |
| 4. Advertise | • Advertise hotline frequently through flyers, magnets, newspapers, displays, etc.<br>• Publicize success stories |
| 5. Respond to complaints | • Provide friendly, knowledgeable customer service<br>• Send an investigator to respond to complaints in a timely manner<br>• Submit incident reports to the hotline database system |
| 6. Track incidents | • Identify recurring problems and suspected offenders<br>• Measure program success<br>• Comply with annual report requirements |

The cost to establish and maintain a hotline varies, but savings can be realized if it can be piggy-backed on an existing community hotline or cost shared with other communities in the region. Also, hotline costs are related to the volume of calls and the staff effort needed for follow-up investigations. A budgeting framework for establish and maintaining a hotline from scratch is provided in Table 25.

### *Illicit Discharge Investigations*

Once an illicit discharge is detected at an outfall or stream, one of four types of illicit discharge investigations is triggered to track down the individual source. These investigations are often time consuming and expensive, require special training and staff expertise, and may result in legal action. They include:

- Storm drain network investigations
- Drainage area investigations
- On-site investigations
- Septic system investigations

Each type of investigation handles a different type of discharge problem and has its advantages and disadvantages. More detail on these investigations is provided in Chapter 13.

#### Storm drain network investigations

Storm drain or "trunk" investigations narrow the source of a discharge problem to a single

<table>
<tr><th colspan="3">Table 25: IDDE Complaint Hotline Costs</th></tr>
<tr><th>Steps</th><th>Initial Cost</th><th>Annual Costs</th></tr>
<tr><td>Define the scope</td><td>$1,500</td><td>$0</td></tr>
<tr><td>Create a tracking and reporting system</td><td>$2,500</td><td>$2,440</td></tr>
<tr><td>Train personnel</td><td>$2,200</td><td>$1,000</td></tr>
<tr><td>Advertise</td><td>$1,500</td><td>$2,920</td></tr>
<tr><td>Respond to complaints</td><td rowspan="2">$0</td><td rowspan="2">$5,000</td></tr>
<tr><td>Track incidents</td></tr>
<tr><td>TOTAL</td><td>$7,700</td><td>$11,360</td></tr>
</table>

segment of a storm sewer. The investigation starts at the outfall, and the field crew must decide how it will explore the upstream pipe network. The three options include:

- Work progressively up the trunk from the outfall and test manholes along the way
- Split the trunk into equal segments and test manholes at strategic points of the storm drain system
- Work progressively down the trunk (i.e., from the headwaters of the storm drain network and move downstream)

The decision to move up, split, or move down the trunk depends on the nature of the drainage system and the surrounding land use. The three options also require different levels of advance preparation. Moving up the trunk can begin immediately when an illicit discharge is detected at an outfall, and only a map of the storm drain system is required. Splitting the trunk requires a little more preparation to examine the storm drain system and find the most strategic manholes to sample. Moving down the trunk requires even more advance preparation, since the most upstream segments of the storm drain network may be poorly understood.

Once crews choose one of these options, they need to select the most appropriate investigative methods to track down the source. Common methods include:

- Visual inspection at manholes
- Sandbagging or damming the trunk
- Dye testing
- Smoke testing
- Video testing

## Drainage area investigations

Drainage area investigations are initially conducted in the office, but quickly move into the field. They involve a parcel by parcel analysis of potential generating sites within the drainage area of a problem outfall. They are most appropriate when the drainage area to the outfall is large or complex, and when the flow type in the discharge appears to be specific to a certain type of land use or generating site. These investigations may include the following techniques:

- Land use investigations
- SIC code review (see Appendix A)
- Permit review
- As-built review
- Aerial photography analysis
- Infrared aerial photography analysis
- Property ownership certification

## On-site investigations

Once the illicit discharge has been isolated to a specific section of storm drain, an on-site investigation can be performed to find the specific source of the discharge. In some situations, such as subwatersheds dominated by industrial land uses or many generating sites, on-site investigations may be immediately pursued.

On-site investigations are typically performed by dye testing the plumbing systems of households and buildings. Where septic systems are prevalent, inspections of tanks and drain fields may be needed.

On-site investigations are excellent opportunities to combine IDDE efforts with industrial site inspections that target review and verification of proper Storm Water

Pollution Prevention Plans. Appendix A provides a list of industrial activities that typically require industrial NPDES discharge permits.

Septic system investigations

Communities with areas of on-site sewage disposal systems (i.e., septic systems) need to consider alternative investigatory methods to track illicit discharges that enter streams as indirect discharges, through surface breakouts of septic fields, or through straight pipe discharges from bypassed septic systems. Techniques can involve on-site investigations or imagery analysis (e.g., infrared aerials).

## 8.3 Fixing Illicit Discharges

Once the source of an illicit discharge has been identified, steps should be taken to fix or eliminate the discharge. Four questions should be answered for each individual illicit discharge to determine how to proceed; the answers will usually vary depending on the source of the discharge.

- Who is responsible?
- What methods will be used to repair?
- How long will the repair take?
- How will removal be confirmed?

Financial responsibility for source removal will typically fall on property owners, MS4 operators, or a combination of the two. Methods for removing illicit discharges usually involve a combination of education and enforcement. A process for addressing illicit discharges that focuses on identifying the responsible party and enforcement procedures is presented in Figure 13, while Table 26 presents various options for removing illicit discharges from various sources. Additional information on common removal actions and associated costs can be found in Chapter 14.

Program managers should use judgment in exercising the right mix of compliance assistance and enforcement. The authority and responsibility for correction and enforcement should be clearly defined in the local IDDE ordinance developed earlier in the program. An escalating enforcement approach is often warranted and is usually a reasonable process to follow. Voluntary compliance should be used for first-time, minor offenders. Often, property owners are not even aware of a problem, and are willing to fix it when educated. More serious violations or continued non-compliance may warrant a more aggressive, enforcement-oriented approach.

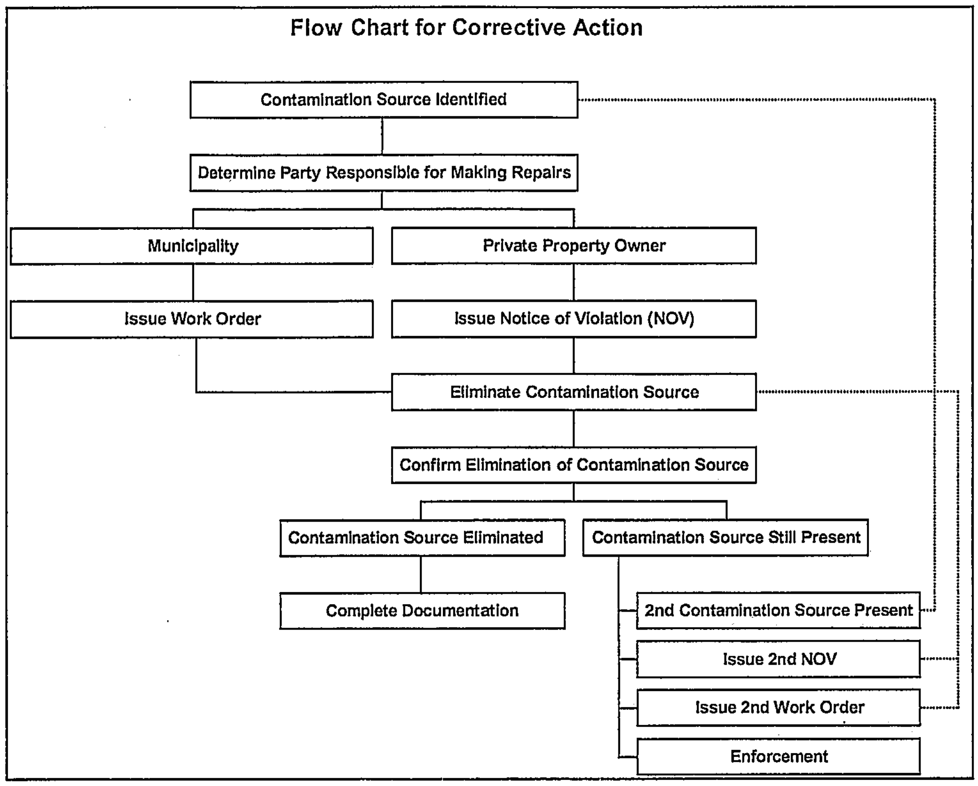
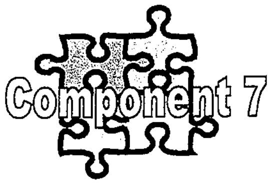



**Figure 13: Process for Removing or Correcting an Illicit Discharge**

**Table 26: Methods to Fix Illicit Discharges**

| Type of Discharge | Source | Removal Action(s) |
|---|---|---|
| **Sewage** | Break in right-of-way | Repair by municipality |
| | Commercial or industrial direct connection | Enforcement |
| | Residential direct connection | Enforcement; Incentive or aid |
| | Infrequent discharge (e.g., RV dumping) | Enforcement; Spill response |
| | Straight pipes/septic | Enforcement; Incentive or aid |
| **Wash water** | Commercial or industrial direct connection | Enforcement; Incentive or aid |
| | Residential direct connection | Enforcement; Incentive or aid |
| | Power wash/car wash (commercial) | Enforcement |
| | Commercial wash down | Enforcement |
| | Residential car wash or household maintenance-related activities | Education |
| **Liquid wastes** | Professional oil change/car maintenance | Enforcement; Spill response |
| | Heating oil/solvent dumping | Enforcement; Spill response |
| | Homeowner oil change and other liquid waste disposal (e.g., paint) | Warning; Education; Fines |
| | Spill (trucking) | Spill response |
| | Other industrial wastes | Enforcement; Spill response |




# Chapter 9: Preventing Illicit Discharges

*Purpose*: This program component identifies key behaviors of neighborhoods, generating sites, and municipal operations that produce intermittent and transitory discharges. These key "discharge behaviors" are then targeted for improved pollution prevention practices that can prevent or reduce the risk of discharge. Communities then apply a wide range of education and enforcement tools to promote the desired pollution prevention practices.

*Method(s):* The Unified Subwatershed and Site Reconnaissance (USSR; Wright *et al.*, 2004) and the desktop analysis of potential generating sites (Chapter 5) are two methods used to identify the major behaviors that generate intermittent and transitory discharges. These methods, used alone or in combination, are extremely helpful to identify the specific discharge behaviors and generating sites that will be targeted for education and enforcement efforts. A Source Control Plan is then performed to select the right pollution prevention message, choose the appropriate combination of carrots and sticks to change behaviors, and develop a budget and delivery system to implement the prevention program. Refer to Schueler *et al.* (2004) for information on developing a Source Control Plan and the many carrots and sticks available to communities.

*Desired Product or Outcome(s):* The desired outcome is a mix of local prevention programs that target the most common intermittent and transitory discharges in the community. Program managers need to develop targeted pollution prevention programs for three sectors of the community:

- *Neighborhood Discharges.* The pollution prevention practices related to discharge prevention in residential neighborhoods include storm drain stenciling, lawn care, septic system maintenance, vehicle fluid changing, car washing, household hazardous waste disposal and swimming pool draining.
- *Generating Sites.* This group of pollution prevention practices can reduce spills and transitory discharges generated during common business operations. Practices include business outreach, spill prevention and response plans, employee training and site inspections.
- *Municipal Housekeeping.* This group of pollution prevention practices is performed during municipal operations, such as sewer and storm drain maintenance, plumbing code revision, and provision of household hazardous waste and used oil collection services.

*Budget and/or Staff Resources Required*: The budget and staff resources needed for prevention programs can be considerable, and should be coordinated with other storm water education, public involvement and municipal housekeeping initiatives required under NPDES Phase II MS4 permits. Special emphasis should be placed on cross-training staff, partnering with local watershed groups, and pooling educational resources with other communities.

*Integration with Other Programs*: Illicit discharge prevention is linked to three of the six NPDES Phase II minimum management measures, and should be closely integrated with local watershed restoration efforts.

## 9.1 Overview of Preventing Illicit Discharges

Intermittent and transitory discharges are difficult to detect through outfall screening or indicator monitoring. Indeed, the best way to manage these discharges is to promote pollution prevention practices in the community that prevent them from occurring. Effective IDDE programs develop education and outreach materials targeted toward neighborhoods, generating sites, and municipal operations. The discharge prevention message is normally integrated with other storm water education programs required under MS4 NPDES Phase II permits such as

- Public education and outreach
- Public participation/involvement
- Municipal pollution prevention/good housekeeping

## 9.2 Methods to Identify Opportunities for Illicit Discharge Prevention

The USSR and the desktop analysis of potential generating sites both help identify the major behaviors that generate intermittent and transitory discharges. These assessment methods are briefly described below:

### *The Unified Subwatershed and Site Reconnaissance (USSR)*

The USSR is a field survey that rapidly evaluates potential pollution sources and restoration potential in urban subwatersheds. The survey quickly characterizes upland areas in order to inventory problem sites that may contribute pollutants and identifies pollution source controls and other restoration projects. For more information on how to conduct the USSR, consult Wright *et al.* (2004). The USSR has four major assessment components, three of which directly relate to illicit discharge prevention:

- *Neighborhood Source Assessment (NSA)*, which helps discover residential pollution source areas and potential restoration opportunities within the many neighborhoods found in urban subwatersheds
- *Hotspot Site Investigation (HSI)*, which ranks the potential severity of each commercial, industrial, institutional, municipal or transport-related hotspot site found within a subwatershed
- *Analysis of Streets and Storm Drains (SSD)*, which measures the average pollutant accumulation in the streets, curbs, and catch basins of a subwatershed

### *Desktop Analysis of Generating Sites*

The desktop analysis method screens local business and permit databases to identify specific commercial, industrial, institutional, municipal, and transport-related sites that are known to have a higher risk of producing illicit discharges. Chapter 5 and Appendix A provide discussions of this analysis.

## 9.3 Preventing Illicit Discharges from Neighborhoods

Many common neighborhood behaviors can cause transitory discharges that are seldom defined or regulated as illicit discharges by most communities. Individually, these behaviors cause relatively small discharges, but collectively, they can produce significant pollutant loads. Most communities use outreach and education to promote pollution prevention practices, and some of the more effective practices to influence these behaviors are described in this section:

- Storm drain stenciling
- Septic system maintenance
- Vehicle fluid changing
- Car washing
- Household hazardous waste storage and disposal
- Swimming pool draining

### Storm Drain Stenciling

Storm drain stenciling sends a clear message to keep trash and debris, leaf litter, and pollutants out of the storm drain system, and may deter illegal dumping and discharges (Figure 14). Stenciling may increase watershed awareness and neighborhood stewardship and can be used in any neighborhood with enclosed storm drains.

Stenciling is an excellent way to involve the public, and just a few trained volunteers can systematically stencil all the storm drains within a neighborhood in a short time. Volunteers can be recruited from scouting, community service, and watershed organizations, or from high schools and neighborhood associations. Program managers should designate a staff person to coordinate storm drain stenciling and be responsible for recruiting, training, managing, and supplying volunteers.


**Figure 14: Storm drain stenciling may help reduce illicit discharges.**

Storm drain stenciling programs are relatively inexpensive. Most communities use stencils, although some are now using permanent markers made of tile, clay, or metal. Stencils cost about 45 cents per linear inch and can be used for 25 to 500 drains, depending on whether paint is sprayed or applied with a brush or roller. Permanent signs are generally more costly; ceramic tiles cost \$5 to \$6 each and metal stencils can cost \$100 or more. More guidance on designing a stenciling program can be found in Schueler *et al.* (2004).

### Septic System Maintenance

Failing septic systems can be a major source of bacteria, nitrogen, and phosphorus, depending on the overall density of systems present in a subwatershed (Swann, 2001). Failure results in illicit surface or subsurface discharges to streams. According to U.S. EPA (2002), more than half of all existing septic systems are more than 30 years old, which is well past their design life. The same study estimates that about 10% of all septic systems are not functioning properly at any given time, with even higher failure rates in some regions and soil conditions.

Septic systems are a classic case of out of sight and out of mind. Many owners take their septic systems for granted, until they back up or break out on the surface of their lawn. Subsurface failures, which are the most common, go unnoticed. In addition, inspections, pump outs, and repairs can be costly, so many homeowners tend to put off the expense until there is a real problem. Lastly, many septic system owners are not aware of the link between septic systems

CASE STUDY

In 1997, Madison County, NC implemented a project to address straight piping problems. In 1999, a survey identified 205 households with black water straight-piping (toilet waste), 243 households with gray water straight-piping (sink, shower, washer waste), and 104 households with failing septic systems. The project facilitated more than 10 community meetings, and issued more than 20 educational articles on straight-piping and water quality in the local papers. In addition, the project leveraged $903,000 from the N.C. Clean Water Management Trust Fund to establish a Revolving Loan and Grant Program for low and moderate income county residents that need assistance installing a septic system or repairing a failing one. (Land of Sky Regional Council website, 2002).

and water quality. Communities can employ a range of tools to improve septic system maintenance. These include:

- Media campaigns and conventional outreach materials to increase awareness about septic system maintenance and water quality (e.g., billboards, radio, newspapers, brochures, bill inserts, and newsletters)
- Discount coupons for septic system maintenance
- Low interest loans for septic system repairs
- Mandatory inspections
- Performance certification upon property transfer
- Creation of septic management districts
- Certification and training of operation/maintenance professionals
- Termination of public services for failing systems

### Vehicle Fluid Changing

Dumping of automotive fluids into storm drains can cause major water quality problems, since only a few quarts of oil or a few gallons of antifreeze can severely degrade a small stream. Dumping delivers hydrocarbons, oil and grease, metals, xylene and other pollutants to streams, which can be toxic during dry-weather conditions when existing flow cannot dilute these discharges. The major culprit has been the backyard mechanic who changes his or her own automotive fluids (Figure 15). Communities have a range of tools to prevent illegal dumping of car fluids, including:

- Outreach materials distributed at auto parts store and service stations
- Community oil recycling centers
- Directories of used oil collection stations
- Free or discounted oil disposal containers
- Pollution hotlines
- Fines and other enforcement actions

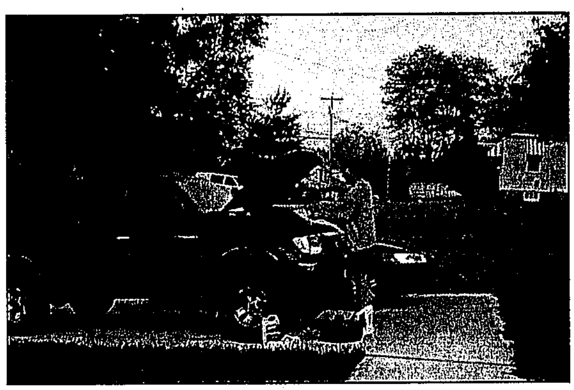


**Figure 15: Home mechanic changing his automotive fluids**

### Car Washing

Car washing is a common neighborhood behavior that can produce transitory discharges of sediment, nutrients and other pollutants to the curb, and ultimately the storm drain. Communities have utilized many innovative outreach tools to promote environmentally safe car washing, including:

- Media campaigns
- Brochures promoting nozzles with shut off valves
- Storm drain plug and wet vac provisions for charity car wash events
- Water bill inserts promoting environmentally safe car washing products
- Discounted tickets for use at commercial car washes

### Household Hazardous Waste Storage And Disposal

The average garage contains a lot of products that are classified as hazardous wastes, including paints, stains, solvents, used motor oil, pesticides and cleaning products. While some household hazardous waste (HHW) may be dumped into storm drains, most enters the storm drain system as a result of outdoor rinsing and cleanup. Improper disposal of HHW can result in acute toxicity to downstream aquatic life. The desired neighborhood behavior is to participate in HHW collection days, and to use appropriate pollution prevention techniques when conducting rinsing, cleaning and fueling operations (Figure 16).

Convenience and awareness appear to be the critical factors in getting residents to participate in household hazardous waste

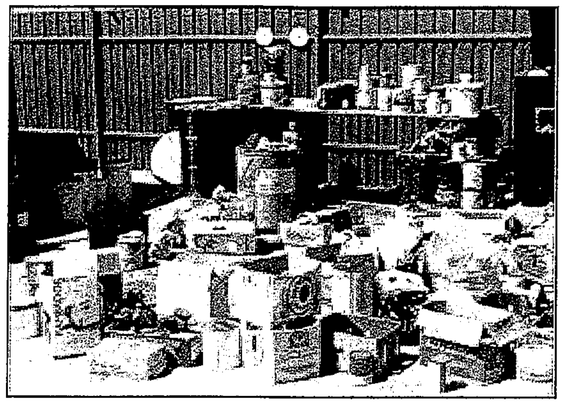


**Figure 16: Household hazardous wastes should be properly contained to avoid indirect discharges**

collection programs. Participation depends on the number of days each year collection events are held and is inversely related to both the distance homeowners must travel to recycle waste and the restrictions on what is accepted. Communities have used a variety of techniques to promote and expand HHW collection, including:

- Mass media campaigns to educate residents about proper outdoor cleaning/rinsing techniques
- Conventional outreach materials notifying residents about HHW and collection days
- More frequent HHW collection days
- Providing curbside disposal options for some HHW
- Establishing permanent collection facilities at solid waste facilities
- Providing mobile HHW pickup
- Waiving disposal fees at landfills

### Swimming Pool Draining

Routine and end-of-season maintenance tasks for aboveground or in-ground pools can cause the discharge of chlorinated water or filter back flush water into the storm drain system or the stream (Figure 17). The ideal practice is to discharge chlorinated pool water into the sanitary sewer system, or hold it until chlorine and temperature levels are acceptable to permit spreading it over a suitable pervious surface.

Most pool owners understand that regular maintenance is essential to keep pools safe and clean, and they may be more receptive to changing discharge behaviors with proper education. Effective outreach methods include:

- Conventional outreach techniques on proper discharge (pamphlets, water bill inserts, posters)
- Educational kiosks at the retail outlets selling pool chemicals
- Changes in local plumbing codes to require discharge to sanitary sewer systems
- Local ordinances that allow for fines/enforcement for unsafe pool discharges

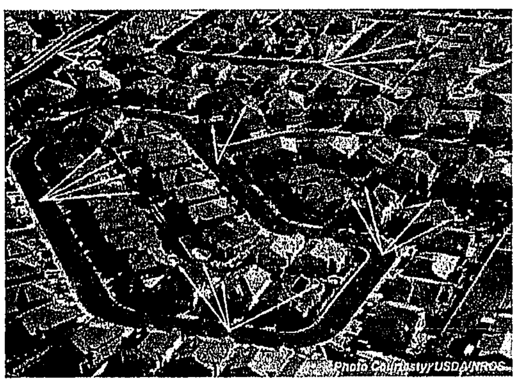


**Figure 17: Swimming pools can be a source of illicit discharges.**

## 9.4 Preventing Illicit Discharges from Generating Sites

Many indirect discharges can be identified and prevented using the concept of generating sites, which are a small subset of commercial, industrial, institutional, municipal and transport-related operations that have the greatest risk of generating indirect discharges. Program managers should become intimately familiar with the types of generating sites found in their community, particularly those regulated by industrial NPDES storm water permits. Some of the more common operations that generate spills and transitory discharges are profiled in Table 27.

Most communities consider nearly all non-storm water discharges from generating sites to be illicit, and take a more regulatory approach. Consequently, pollution prevention practices are more prescriptive, and are frequently incorporated into a pollution prevention plan for a facility or operation. Like anyone else, businesses respond better to carrots than sticks, but often need both. Communities possess four broad tools to promote effective pollution prevention practices at generating sites:

- Business outreach and education
- Spill prevention and response planning
- Employee training
- Site inspections



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| Table 27: Common Discharges Produced at Generating Sites | |
|---|---|
| **Generating Site** | **Activity Generating the Discharge** |
| Vehicle Operations (Maintenance, Repair, Fueling, Washing, Storage) | • Improper disposal of fluids down shop and storm drains<br>• Spilled fuel, leaks and drips from wrecked vehicles<br>• Hosing of outdoor work areas<br>• Wash water from cleaning<br>• Spills |
| Outdoor Materials (Loading/unloading, Outdoor storage) | • Liquid spills at loading areas<br>• Hosing/washing of loading areas into shop or storm drains<br>• Leaks and spills of liquids stored outside |
| Waste Management (Spill prevention and response, Dumpster management) | • Spills and leaks of liquids<br>• Dumping into storm drains<br>• Leaking dumpsters |
| Physical Plant Maintenance (Building Repair, Remodeling and maintenance, Parking lot maintenance) | • Discharges from power washing and steam cleaning<br>• Rinse water and wash water discharges during cleanup<br>• Runoff from degreasing and re-surfacing |
| Turf and Landscaping (Turf Management Landscaping/Grounds care) | • Non-target irrigation<br>• Improper rinsing of fertilizer/pesticide applicators |
| Unique Hotspot Operations (Pools, Golf Courses, Marinas, Construction, Restaurants, Hobby farms) | • Discharge of chlorinated water from pools<br>• Dumping of sewage and grease |

### Business Outreach and Education

Targeted distribution of educational materials to specific business sectors in the subwatershed is the most common method of promoting pollution prevention. Outreach materials are designed to educate owners and employees about polluting behaviors, recommend appropriate pollution prevention practices, and notify them of any local or state regulations. Useful outreach materials include brochures, training manuals, posters, directories of pollution prevention vendors, and signs. Passive business outreach works best when it is specially adapted and targeted to a specific business sector (e.g., vehicle repair, landscaping, restaurants) and is routinely and directly presented to local business groups and trade associations. Business outreach materials require employees to read or hear them, and then take active steps to change their behavior.

Communities can also provide direct technical assistance to develop a customized pollution prevention prescription for individual generating sites. In this case, local staff work closely with owners and operators to inspect the site and develop an effective pollution prevention plan. In other cases, pollution prevention workshops or model plans are offered to businesses and trade groups that represent specific groups of generating sites. In either case, the locality acts as a technical partner to provide ongoing consultation to individual businesses to support their pollution prevention efforts.

## *Spill Prevention and Response*

A spill prevention and response plan is useful for any potential generating site, and is mandatory for any operation that uses, generates, produces, or transports hazardous materials, petroleum products or fertilizers. These operations are known as SARA 312 operators and are regulated by state environmental agencies. In addition, all industrial sites regulated by individual or group NPDES storm water permits must have an updated spill prevention and response plan on its premises. Spill containment and response plans should also be prepared for major highways that cross streams and other water bodies, since truck and tanker accidents often represent the greatest potential spill risk in most communities (Figure 18).

Spill prevention and response plans describe the operational procedures to reduce the risks of spills and accidental discharge and ensure that proper controls are in place in the event they do occur. Spill prevention plans standardize everyday procedures and rely on employee training to reduce potential liability, fines and costs associated with clean up. Planning begins with an analysis of how pollutants are handled at the site and how they interact with storm water. Spill prevention and response plans have five major components:

1. A site map and evaluation of past spills and leaks
2. An inventory of materials at the site
3. Identification of potential spill areas
4. A list of required spill response equipment
5. Employee training

When spills do occur, a good spill prevention and response plan will clearly:

- Identify potential spill sites and their drainage points
- Specify material handling procedures
- Describe spill response procedures
- Ensure that adequate spill clean-up equipment is available

## *Employee Training*

Effective and repeated employee training is essential to maintain pollution prevention practices at generating sites. Indeed, continuous employee training is an essential component of any pollution prevention plan, particularly at generating sites where the work force turns over frequently. Many businesses perceive time devoted to pollution prevention training as reducing their bottom line, and may be hesitant to develop training materials or allocate time for training. In some cases, local agencies supply free or low cost videos, posters, shop signs, or training brochures (often in multilingual formats). In other cases, short training classes are offered for employees or supervisors that are scheduled for down times of the year (e.g., winter classes for landscaping companies or construction contractors) or coincide with regular employee safety meetings.

**Figure 18: Spill response often involves portable booms and pumps**

Program managers can refer to Schueler *et al.* (2004) for more guidance on developing effective pollution practices at generating sites and storm water hotspots. Employee training should be conducted at least annually to educate workers on the proper practices to avoid illicit discharges and respond to spills. Training can be reinforced with signs, and posters.

### Site Inspections

Regular inspections of generating sites are a key tool to foster pollution prevention and reduce the risk of illicit discharges. Communities that possess an MS4 permit should ensure that they have the authority to inspect non-regulated sites that connect to the municipal storm drain system they operate. These inspections can be used to assess the site and educate owners/operators about recommended pollution prevention practices. Site inspections are staff intensive and therefore are best suited to high-risk generating sites.

An industrial NPDES storm water permit is an extremely important compliance tool at many generating sites. NPDES permits require operators to prepare a pollution prevention plan for the site and implement the practices specified in the plan. Significant penalties can be imposed for non-compliance.

To date, compliance with the industrial storm water permit program has been spotty, and a significant fraction of regulated industries has failed to file their required permits. According to Duke and Shaver (1999) and Pronold (2000), as many as 50% of industrial sites that are required to have a permit do not actually have one. These sites are termed "non-filers," and are often small businesses or operations that are unaware of the relatively new regulations. It is therefore quite likely that many hotspots in a subwatershed may not have a valid NPDES permit. These operations should be educated about the industrial permit program, and encouraged to apply for permit coverage. Non-filers should be referred to the NPDES permitting authority for details on how to obtain permit coverage.

Inspections are an important stick to improve compliance at generating sites subject to industrial NPDES permits. Inspectors should frequently observe site operations to ensure that the right mix of pollution prevention practices is routinely employed. Communities with MS4 permits have the authority to inspect storm water NPDES sites that discharge to their storm drain system, and refer any violations for subsequent state or federal enforcement.

Voluntary inspections of non-regulated generating sites are a good tool to educate owners/operators about recommended pollution prevention practices. When generating sites are inspected, existing fire, building or health inspectors should be considered since they are already acquainted with how to deal with small businesses.

## 9.5 Preventing Illicit Discharges from Municipal Operations

Many municipal operations and services have the potential to create or reduce illicit discharges. Program managers should review all municipal operations and services to make sure good housekeeping is practiced. In addition, program managers should examine:

- Routine sewer and storm drain maintenance
- Plumbing code revisions
- HHW collection services
- Used motor oil collection services

### Routine Sewer And Storm Drain Maintenance

Failure to regularly inspect and maintain local sewer and storm water infrastructure can cause illicit discharges to receiving waters. Within the storm drain system, maintenance should focus on frequent cleaning to keep trash, debris and illegally dumped material from entering the storm drain system. In the sanitary sewer network, maintenance should focus on finding damaged infrastructure that allows sewage discharges from the sanitary sewer. In-stream monitoring, historical data reviews of past complaints, or aging sewer infrastructure can often be used to identify likely problem areas.[8]

### Plumbing Code Revisions

Communities need to establish the legal authority to prohibit illicit connections to the storm drain system. When the illicit discharge ordinance is being prepared, communities should thoroughly review all of their plumbing codes to prevent any misinterpretation that might create cross connections to the storm drain system. Program managers should also specifically target licensed plumbers to educate them on any code changes.

### Household Hazardous Waste Collection Services

Households generate a lot of hazardous wastes, and communities need to educate residents about proper household hazardous waster (HHW) handling and disposal, and provide convenient options for pick up and disposal. Communities have experimented with several innovative ways to deal with HHW including:

- A permanent facility that accepts HHW year-round and can serve as a central location for HHW exchange and recycling
- Mobile collection at temporary facilities. On designated special collection days, mobile units can move through communities accepting HHW and take the form of curbside pickup or central collection locations
- Some local businesses may act as drop off centers for certain products. Some local garages, for example, may accept used motor oil for recycling

Overall, the costs for implementing HHW collection programs can be high. Factors such as frequency of the collection, size of community, environmental awareness, level of staff training, and level of outreach all contribute to the overall cost. Participation in collection programs usually ranges from 1% to 5% of the population (HGAC, 2001), and the cost per participant can vary greatly (Table 28).

### Used Motor Oil Collection Services

Used motor oil collection has been a common municipal service for many years, however, program managers may need to refine their programs to increase participation. Suggested outreach approaches include:

- Conventional outreach materials provided at points of sale (e.g., auto parts stores, service stations)
- Multilingual outreach materials
- Directories of used oil collection stations
- Free or discounted oil disposal containers

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[8] Preliminary sewer system investigations are not discussed further in this manual. For more detail on how to conduct these investigations consult the EPA handbook, "Sewer System Infrastructure Analysis and Rehabilitation." (U.S. EPA, 1991)

**CASE STUDY**

The City of Denver operates a pilot, door-to-door collection program to assist residents in the proper disposal and recycling of HHW. To be eligible for collection, residents must currently be receiving trash collection service from City Solid Waste Management crews. Residents are permitted one HHW collection annually and are asked to have at least three different materials before calling for a pickup. Residents then receive a collection date and an HHW Kit that holds up to 75 pounds. Residents are instructed on what items can be placed inside the Kit, and can have additional items picked up for a small fee. The program also educates citizens on how to prevent the accumulation of chemicals in the home environment. The key element of this service is convenience for area residents. Customers can make a phone call, put their waste in a container, and schedule a pickup (City of Denver, 2003).

**Table 28: Summary of Local Household Hazardous Waste Collection Programs**

| Location | Budget | Households Served | Participants | Cost per Participant | Program Description |
|---|---|---|---|---|---|
| Fort Worth TX (2002) | $937,740 | 26 cities | 15,629 | $60 | Accept 3 days a week at permanent facility, plus approx 24 mobile units |
| Monmouth County, NJ (2002) | $900,000 | 620,000 | 6,200 | $145.16 | Permanent facility plus 2-3 remote days |
| Nashville, TN (2002) | $149,000 | 180,000 | 5,800 | $26 | 361 day drop off at permanent facility |
| Putnam County, NY (1997) | $20,279 | 27,409 | 349 | $58.10 | One collection day per year |
| Town of East Hampton, NY (1997) | $36,495 | 4,878 | 452 | $80 | Three collection days per year |

**CASE STUDY**

Municipal cross-training is a proven and effective tool for identifying illicit discharges. Wayne County, Michigan has a very active IDDE program that has included efforts to train all County "field" staff to identify and report suspicious discharges in the course of their duties. The Illicit Discharge Elimination Training Program includes presentations for general field staff that instructs them in the identification and reporting of suspicious discharges. To date, 734 people from various agencies and communities throughout Michigan have attended the training sessions (Tuomari and Thompson, 2002). The information these individuals gained from attending the training session helped identify 82 illicit discharges in the counties of Oakland, Washtenaw, and Wayne. Road division staff trained in recognizing illicit discharges discovered 12 septic systems in Wayne County that were failing or had direct discharges to surface water. Other counties found 70 illicit discharges during their investigations. The elimination of these illicit discharges will prevent an estimated 3.5 million gallons of polluted water from reaching Michigan surface waters each year (associated load reductions are estimated at 7,200 pounds/year of Biological Oxygen Demand and 25, 000 lbs/yr of Total Suspended Solids).

## 9.6 Budgeting and Scoping Pollution Prevention

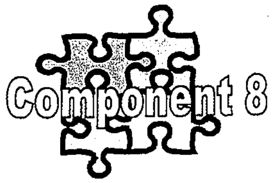
The cost of preventing illicit discharges is directly related to the scope of the education effort. Larger communities often employ education staff on a full-time basis, or at least have one staff member who spends much of their time doing outreach on issues such as illicit discharges. Smaller communities often spread the education effort out over several departments, and try to use already established programs such as cooperative extensions or citizen watershed groups. Table 29 provides some cost data for storm water education in one community.

In reality, program managers have to do a lot of homework to scope and budget their pollution prevention education program. Normally, these education efforts are integrated with other storm water education programs. One of the best tools to develop an overall education budget is the Source Control Plan, which is described in Schueler *et al.* (2004).

**Table 29: Estimated Costs for Public Awareness Program Components**
***(Adapted from Wayne County, MI. 2001)***

| Education Component | Estimated Cost | Assumptions |
|---|---|---|
| Information Brochures | \$100/hour for development<br>\$0.10-\$0.20/pamphlet for black and white printing<br>\$0.30/pamphlet for mailing | 160-320 hours |
| Technical Manuals | \$100/hour for development<br>\$100.00/manual for printing | 160-480 hours |
| Business Education | \$50/hour for business/activity list<br>\$100/hour for development<br>\$50/hour for employee presentation | 40-80 hours for compilation<br>80-160 hours for development.<br>8 hours for presentation, including prep time. |
| Program Planning and Administration | \$10,000 per year | 0.2 Full Time Equivalents (FTE) per year |

*Source: Wayne County, MI. 2001.* Planning and Cost Estimating Criteria for Best Management Practices. *Rouge River Wet Weather Demonstration Project. TR-NPS25.00*




# Chapter 10: IDDE Program Tracking and Evaluation

*Purpose:* This last program component addresses the ongoing management of the IDDE program and reviews progress made in meeting the measurable program goals established earlier in the permit cycle. Adaptive management is critical since most communities initially have a poor understanding of the scope and nature of their illicit discharge problem. Frequent program review can ensure that the most severe illicit discharges are eliminated in the most cost-effective way during the permit cycle. Program evaluation should also be directly tied to program goals (see Chapter 6 on Developing Program Goals and Implementation Strategy)

*Method(s):* The primary method is frequent maintenance and analysis of the IDDE tracking system developed as part of the program. The integrated tracking system contains geospatial data on ORI results, indicator monitoring, on-site investigations, dumping and spill sites and hotline calls. The tracking system is important from both an enforcement and program evaluation standpoint. Each of the eight program components should be reviewed annually and prior to new permit negotiation, using data collected, compiled, and assessed from the tracking system.

*Desired Product or Outcome(s):* Updated tracking database and annual report with summary of progress to date, findings, recommendations for program revisions, and work plan (including milestones and goals) for the upcoming year.

*Budget and/or Staff Resources Required*: Program assessment is an ongoing responsibility of the program manager. The staff effort to prepare an annual report is about three to four weeks. In general, the first annual report will require more effort than subsequent ones.

*Integration with Other Programs*: Program managers should always consider other programs and regulatory requirements when assessing program performance and revising goals. At a minimum, the annual report should be shared with other departments and agencies to head off duplication of efforts and to look for opportunities to pool resources.

## 10.1 Establish a Tracking and Reporting System

An accurate and user-friendly system to track, report and respond to illicit discharge problems is critical for program managers. Ideally, the tracking system should be designed and operational within the first year of the program. The tracking system enables managers to measure program indicators, and gives field crews a home to store the data they collect. The ideal tracking system consists of a relational database that is linked to a GIS system, which can be used to store and analyze data and produce maps.

The fundamental units to track are individual outfalls, along with any supporting information about their contributing drainage area. Some of the key information to include when tracking outfalls includes:

- Geospatial coordinates of each outfall location
- The subwatershed and watershed address
- Any supporting information about the contributing land use
- Diameter and physical characteristics of the outfall
- Outfall Reconnaissance Inventory (ORI) data, as it is collected
- Any accompanying digital photos
- Any follow-up monitoring at the outfall or further up the pipe
- Any hotline complaints logged for the outfall, along with the local response
- Status and disposition of any enforcement actions
- Maintenance and inspection data

## 10.2 Evaluate the Program

Since IDDE programs are a first time endeavor for many communities, program managers need to be extremely adaptable in how they allocate their resources. Effective IDDE programs are dynamic and flexible to respond to an ever-changing set of discharge problems, program obstacles, and emerging technologies. At a minimum, program managers should maintain and evaluate their IDDE tracking system annually, and modify program components as needed. Tracking systems should be designed so that progress toward measurable goals (see Chapter 6) can be easily reported. Communities that develop and maintain a comprehensive tracking system should realize program efficiencies. The tracking system should contain the following features at a minimum:

- Updated mapping to reflect outfalls located during the ORI
- Surveyed stream reaches with locations of obvious, suspect, and potential discharges, and locations of dumping sites
- Indicator sampling results for specific streams, outfalls and storm drains
- Frequency of hotline use and associated number of "hits" or confirmed illicit discharges
- Costs for each of the eight program components (e.g., office, field, lab, education, enforcement, etc.)
- Number of discharges corrected
- Status and disposition of enforcement actions

Regular analysis of the tracking system sheds light on program strengths and deficiencies, and improves targeting of limited program resources. For example, if hotline complaints are found to uncover the most severe illicit discharge problems, program managers may want to allocate more resources to increase public awareness about the hotline, and shift resources from outfall screening and indicator monitoring.

# Chapter 11: The Outfall Reconnaissance Inventory

This chapter describes a simple field assessment known as the Outfall Reconnaissance Inventory (ORI). The ORI is designed to fix the geospatial location and record basic characteristics of individual storm drain outfalls, evaluate suspect outfalls, and assess the severity of illicit discharge problems in a community. Field crews should walk all natural and man-made streams channels with perennial and intermittent flow, even if they do not appear on available maps (Figure 19). The goal is to complete the ORI on every stream mile in the MS4 within the first permit cycle, starting with priority subwatersheds identified during the desktop analysis. The results of the ORI are then used to help guide future outfall monitoring and discharge prevention efforts.

## 11.1 Getting Started

The ORI requires modest mapping, field equipment, staffing and training resources. A complete list of the required and optional resources needed to perform an ORI is presented in Table 30. The ORI can be combined with other stream assessment tools, and may be supplemented by simple indicator monitoring. Ideally, a Phase II community should plan on surveying its entire drainage network at least once over the course of each five-year permit cycle. Experience suggests that it may take up to three stream walks to identify all outfalls.

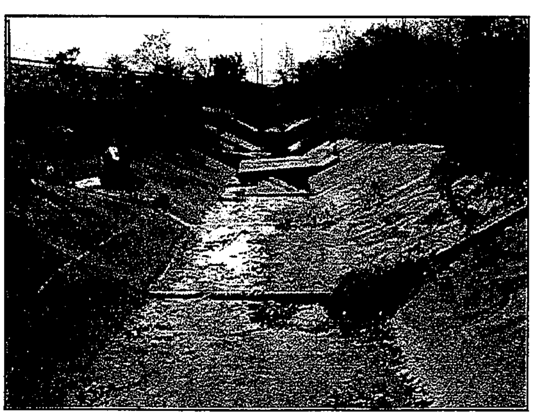


**Figure 19: Walk all streams and constructed open channels**

### *Best Times to Start*

Timing is important when scheduling ORI field work. In most regions of the country, spring and fall are the best seasons to perform the ORI. Other seasons typically have challenges such as over-grown vegetation or high groundwater that mask illicit discharges, or make ORI data hard to interpret[9].

Prolonged dry periods during the non-growing season with low groundwater levels are optimal conditions for performing an ORI. Table 31 summarizes some of the regional factors to consider when scheduling ORI surveys in your community. Daily weather patterns also determine whether ORI field work should proceed. In general, ORI field work should be conducted at least 48 hours after the last runoff-producing rain event.

### *Field Maps*

The field maps needed for the ORI are normally generated during the desktop assessment phase of the IDDE program described in Chapter 5. This section provides guidance on the basic requirements for good

[9] Upon initial program start-up, the ORI should be conducted during periods of low groundwater to more easily identify likely illicit discharges. However, it should be noted that high water tables can increase sewage contamination in storm drain networks due to infiltration and inflow interactions. Therefore, in certain situations, seasonal ORI surveys may be useful at identifying these types of discharges. Diagnosis of this source of contamination, however, can be challenging.

| Table 30: Resources Needed to Conduct the ORI | | |
|---|---|---|
| **Need Area** | **Minimum Needed** | **Optional but Helpful** |
| **Mapping** | • Roads<br>• Streams | • Known problem areas<br>• Major land uses<br>• Outfalls<br>• Specific industries<br>• Storm drain network<br>• SIC-coded buildings<br>• Septics |
| **Field Equipment** | • 5 one-liter sample bottles<br>• Backpack<br>• Camera (preferably digital)<br>• Cell phones or hand-held radios<br>• Clip boards and pencils<br>• Field sheets<br>• First aid kit<br>• Flash light or head lamp<br>• GPS unit<br>• Spray paint (or other marker)<br>• Surgical gloves<br>• Tape measure<br>• Temperature probe<br>• Waders (snake proof where necessary)<br>• Watch with a second hand | • Portable Spectrophotometer and reagents (can be shared among crews)<br>• Insect repellant<br>• Machete/clippers<br>• Sanitary wipes or biodegradable soap<br>• Wide-mouth container to measure flow<br>• Test strips or probes (e.g., pH and ammonia) |
| **Staff** | • Basic training on field methodology<br>• Minimum two staff per crew | • Ability to track discharges up the drainage system<br>• Knowledge of drainage area, to identify probable sources.<br>• Knowledge of basic chemistry and biology |

| Table 31: Preferred Climate/Weather Considerations for Conducting the ORI | | |
|---|---|---|
| **Preferred Condition** | **Reason** | **Notes/Regional Factors** |
| Low groundwater (e.g., very few flowing outfalls) | High groundwater can confound results | In cold regions, do not conduct the ORI in the early spring, when the ground is saturated from snowmelt. |
| No runoff-producing rainfall within 48 hours | Reduces the confounding influence of storm water | The specific time frame may vary depending on the drainage system. |
| Dry Season | Allows for more days of field work | Applies in regions of the country with a "wet/dry seasonal pattern." This pattern is most pronounced in states bordering or slightly interior to the Gulf of Mexico or the Pacific Ocean. |
| Leaf Off | Dense vegetation makes finding outfalls difficult | Dense vegetation is most problematic in the southeastern United States.<br>This criterion is helpful but not required. |

field maps. First, ORI field maps do not need to be fancy. The scale and level of mapping detail will vary based on preferences and navigational skills of field crews. At a minimum, maps should have labeled streets and hydrologic features (USGS blue line streams, wetlands, and lakes), so field crews can orient themselves and record their findings spatially.

Field maps should delineate the contributing drainage area to major outfalls, but only if they are readily available. Urban landmarks such as land use, property boundaries, and storm drain infrastructure are also quite useful in the field. ORI field maps should be used to check the accuracy and quality of pre-existing mapping information, such as the location of outfalls and stream origins.

Basic street maps offer the advantage of simplicity, availability, and well-labeled road networks and urban landmarks. Supplemental maps such as a 1": 2000' scale USGS Quad sheet or finer scale aerial photograph are also recommended for the field. USGS Quad sheets are readily available and display major transportation networks and landmarks, "blue line" streams, wetlands, and topography. Quad maps may be adequate for less developed subwatersheds, but are not always accurate in more urban subwatersheds.

Recent aerial photographs may provide the best opportunity to navigate the subwatershed and assess existing land cover. Aerial photos, however, may lack topography and road names, can be costly, and are hard to record field notes on due to their darkness. GIS-ready aerial photos and USGS Quad sheets can be downloaded from the internet or obtained from local planning, parks, or public works agencies.

### *Field Sheets*

ORI field sheets are used to record descriptive and quantitative information about each outfall inventoried in the field. Data from the field sheets represent the building blocks of an outfall tracking system allowing program managers to improve IDDE monitoring and management. A copy of the ORI field sheet is provided in Appendix D, and is also available as a Microsoft Word™ document. Program managers should modify the field sheet to meet the specific needs and unique conditions in their community.

Field crews should also carry an authorization letter and a list of emergency phone numbers to report any emergency leaks, spills, obvious illicit discharges or other water quality problems to the appropriate local authorities directly from the field. Local law enforcement agencies may also need to be made aware of the field work. Figure 20 shows an example of a water pollution emergency contact list developed by Montgomery County, MD.

### *Equipment*

Basic field equipment needed for the ORI includes waders, a measuring tape, watch, camera, GPS unit, and surgical gloves (see Table 30). GPS units and digital cameras are usually the most expensive equipment items; however, some local agencies may already have them for other applications. Adequate ranging, water-resistant, downloadable GPS units can be purchased for less than $150. Digital cameras are preferred and can cost between $200 and $400, however, conventional or disposable cameras can also work, as long as they have flashes. Hand-held data recorders and customized software can be used to record text, photos, and GPS coordinates electronically in the field. While these technologies can eliminate field sheets and data entry procedures, they can be quite expensive. Field crews should always carry basic safety items, such as cell phones, surgical gloves, and first aid kits.

### Staffing

The ORI requires at least a two-person crew, for safety and logistics. Three person crews provide greater safety and flexibility, which helps divide tasks, allows one person to assess adjacent land uses, and facilitates tracing outfalls to their source. All crew members should be trained on how to complete the ORI and should have a basic understanding of illicit discharges and their water quality impact. ORI crews can be staffed by trained volunteers, watershed groups and college interns. Experienced crews can normally expect to cover two to three stream miles per day, depending on stream access and outfall density.

## 11.2 Desktop Analysis to Support the ORI

Two tasks need to be done in the office before heading out to the field. The major ORI preparation tasks include estimating the total stream and channel mileage in the subwatershed and generating field maps. The total mileage helps program managers scope out how long the ORI will take and how much it will cost. As discussed before, field maps are an indispensable navigational aid for field crews working in the subwatershed.

### Delineating Survey Reaches

ORI field maps should contain a preliminary delineation of **survey reaches**. The stream network within your subwatershed should be delineated into discrete segments of relatively uniform character. Delineating

**WATER POLLUTION PHONE NUMBERS TO CALL WHEN A WATER QUALITY PROBLEM IS OBSERVED or TO OBTAIN FURTHER INFORMATION ABOUT WATER QUALITY ISSUES**
**Spring 2001**

**COUNTY AGENCIES**

- DEP: Department of Environmental Protection
  - DEPC: Division of Environmental Policy & Compliance
  - WMD: Watershed Management Division
- DPS: Department of Permitting Services
  - LDS: Land Development Services
  - SWM: Stormwater Management
  - WS: Wells & Septic

**INTER-COUNTY AGENCIES**

- MNCPPC: Maryland-National Capital Park & Planning Commission
- WSSC: Washington Suburban Sanitary Commission
- DHCD: Department of Housing & Community Development
- DPWT: Department of Public Works & Transportation

| PROBLEM/QUESTION | AGENCY | TELEPHONE NUMBER |
|---|---|---|
| **ILLEGAL DUMPING HOTLINE** | DEPC: | 240-777-7700 Daytime hours |
| | Nighttime hours | 240/777-DUMP (3867) or 240-777-7788 |
| Blocked storm drain, inlet or pipe or erosion from public storm drain | DPWT: | 240/777-ROAD (7623) Highway Maintenance) |
| Discolored public drinking water, odor to drinking water | | 301/206-4002 |
| Erosion, flooding, drainage problems between private properties | DHCD: | 240/777-3600 (Code Enforcement) |
| Erosion - stream banks on park land | MNCPPC: | 301/495-2535 |
| Fire & Rescue Services (emergencies: 911) | (Non-Emergencies): | 240/777-0744 |
| Recycling Programs/Special pick up services | DPWT: | 240/777-6400 or 6466 |
| Sanitary sewer problems | WSSC: | 301/206-4002 |
| Sediment (mud) from construction site entering streams | LDS: | 240/777-6366 |
| Septic Leaks/ Septic Tanks | WS: | 240/777-6300 |
| Stormwater Management, pond safety and maintenance | DEPC: | 240/777-7744 |
| Stormwater Management and Sediment Control Plan Review issues | SWM: | 240/777-6320 |
| Stream Clean-ups | WMD: | 240/777-7712 |
| Swimming Pool Discharges | DEPC: | 240/777-7770 |
| Trash and debris in parks and streams | MNCPPC: | 301/495-2535 |
| Water main break | WSSC: | 301/206-4002 |
| Water pollution | DEPC: | 240/777-7770 |
| (discharging, dumping, chemical spills into streams or storm drains) | LDS: | 240/777-6260 |
| Water quality monitoring programs for schools (Stream Teams) | WMD: | 240/777-7714 |
| Wells and Well Inspections | WS: | 240/777-6300 |

askDEP.com

**Figure 20: Example of a comprehensive emergency contact list for Montgomery County, MD**



A006102

survey reaches provides good stopping and starting points for field crews, which is useful from a data management and logistics standpoint. Each survey reach should have its own unique identifying number to facilitate ORI data analysis and interpretation. Figure 21 illustrates some tips for delineating survey reaches, and additional guidance is offered below:

- Survey reaches should be established above the confluence of streams and between road crossings that serve as a convenient access point.
- Survey reaches should be defined at the transition between major changes in land use in the stream corridor (e.g. forested land to commercial area).
- Survey reaches should generally be limited to a quarter mile or less in length. Survey reaches in lightly developed subwatersheds can be longer than those in more developed subwatersheds, particularly if uniform stream corridor conditions are expected throughout the survey reach.
- Access through private or public property should be considered when delineating survey reaches as permission may be required.

It should be noted that initial field maps are not always accurate, and changes may need to be made in the field to adjust survey reaches to account for conditions such as underground streams, missing streams or long culverts. Nevertheless, upfront time invested in delineating survey reaches makes it easier for field crews to perform the ORI.

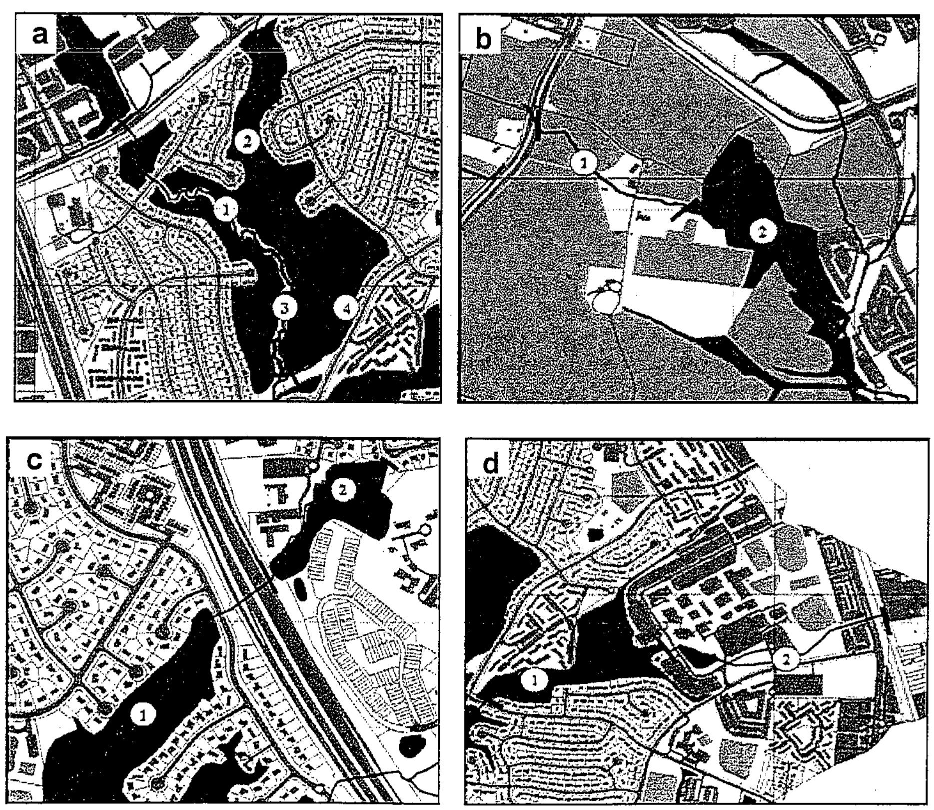



**Figure 21:** Various physical factors control how survey reaches are delineated. (a) Survey reaches based on the confluence of stream tributaries. (b) A long tributary split into ¼ mile survey reaches. (c) Based on a major road crossing (include the culvert in the downstream reach). (d) Based on significant changes in land use (significant changes in stream features often occur at road crossings, and these crossings often define the breakpoints between survey reaches).

## 11.3 Completing the ORI

Field crews conduct an ORI by walking all streams and channels to find outfalls, record their location spatially with a GPS unit and physically mark them with spray paint or other permanent marker. Crews also photograph each outfall and characterize its dimensions, shape, and component material, and record observations on basic sensory and physical indicators. If dry weather flow occurs at the outfall, additional flow and water quality data are collected. Field crews may also use field probes or test strips to measure indicators such as temperature, pH, and ammonia at flowing outfalls.
The ORI field sheet is divided into eight sections that address both flowing and non-flowing outfalls (Appendix D). Guidance on completing each section of the ORI field sheet is presented below.

### *Outfalls to Survey*

The ORI applies to **all** outfalls encountered during the stream walk, regardless of diameter, with a few exceptions noted in Table 32. Common outfall conditions seen in communities are illustrated in Figure 22 As a rule, crews should only omit an outfall if they can definitively conclude it has no potential to contribute to a transitory illicit discharge. While EPA's Phase I guidance only targeted major outfalls (diameter of 36 inches or greater), documenting all outfalls is recommended, since smaller pipes make up the majority of all outfalls and frequently have illicit discharges (Pitt *et al.*, 1993 and Lalor, 1994). A separate ORI field sheet should be completed for each outfall.

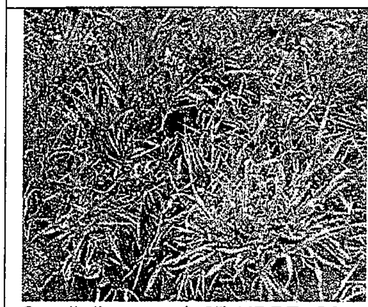
**Table 32: Outfalls to Include in the Screening**

| Outfalls to Record | Outfalls to Skip |
|---|---|
| • Both large and small diameter pipes that appear to be part of the storm drain infrastructure<br>• Outfalls that appear to be piped headwater streams<br>• Field connections to culverts<br>• Submerged or partially submerged outfalls<br>• Outfalls that are blocked with debris or sediment deposits<br>• Pipes that appear to be outfalls from storm water treatment practices<br>• Small diameter ductile iron pipes<br>• Pipes that appear to only drain roof downspouts but that are subsurface, preventing definitive confirmation | • Drop inlets from roads in culverts (unless evidence of illegal dumping, dumpster leaks, etc.)<br>• Cross-drainage culverts in transportation right-of-way (i.e., can see daylight at other end)<br>• Weep holes<br>• Flexible HDPE pipes that are known to serve as slope drains<br>• Pipes that are clearly connected to roof downspouts via above-ground connections |

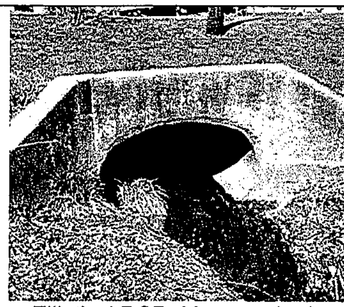
Ductile iron round pipe

4-6" HDPE; Check if roof leader connection (legal)

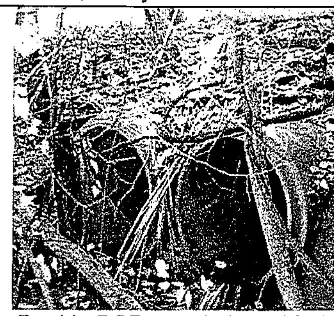
Field connection to inside of culvert; Always mark and record.



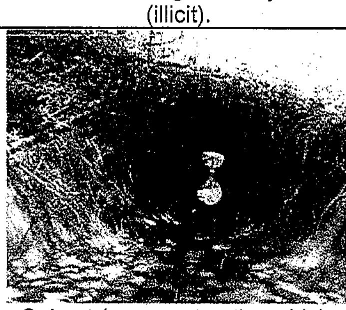
Small diameter (<2") HDPE; Often a sump pump (legal), or may be used to discharge laundry water (illicit).



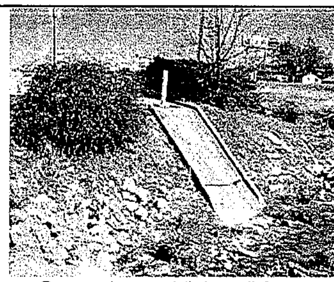
Elliptical RCP; Measure both horizontal and vertical diameters.



Double RCP round pipes; Mark as separate outfalls unless known to connect immediately up-pipe

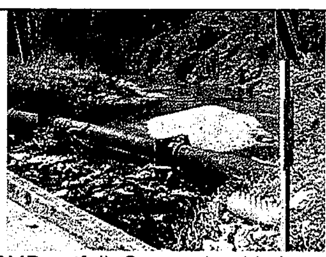


Culvert (can see to other side); Don't mark as an outfall.

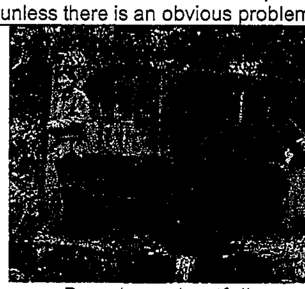


Open channel "chute" from commercial parking lot; Very unlikely illicit discharge. Mark, but do not return to sample (unless there is an obvious problem).

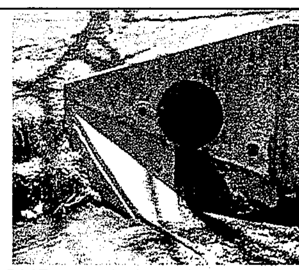
Small diameter PVC pipe; Mark, and look up-pipe to find the origin.



CMP outfall; Crews should also note upstream sewer crossing.



Box shaped outfall



CMP round pipe with two weep holes at bridge crossing. (Don't mark weep holes)

**Figure 22: Typical Outfall Types Found in the Field**

### *Obvious Discharges*

Field crews may occasionally encounter an obvious illicit discharge of sewage or other pollutants, typified by high turbidity, odors, floatables and unusual colors. When obvious discharges are encountered, field crews should STOP the ORI survey, track down the source of the discharge and immediately contact the appropriate water pollution agency for enforcement. Crews should photo-document the discharge, estimate its flow volume and collect a sample for water quality analysis (if this can be done safely). All three kinds of evidence are extremely helpful to support subsequent enforcement. Chapter 13 provides details on techniques to track down individual discharges.

## 11.4 ORI Section 1 - Background Data

The first section of the ORI field sheet is used to record basic data about the survey, including time of day, GPS coordinates for the outfall, field crew members, and current and past weather conditions (Figure 23). Much of the information in this section is self-explanatory, and is used to create an accurate record of when, where, and under what conditions ORI data were collected. Every outfall should be photographed and marked by directly writing a unique identifying number on each outfall that serves as its subwatershed "address" (Figure 24). Crews can use spray paint or another temporary marker to mark outfalls, but may decide to replace temporary markings with permanent ones if the ORI is repeated later. Markings help crews confirm outfall locations during future investigations, and gives citizens a better way to report the location of spills or discharges when calling a water pollution hotline. Crews should mark the spatial location of all outfalls they encounter directly on field maps, and record the coordinates with a GPS unit that is accurate to within 10 feet. Crews should take a digital photo of each outfall, and record photo numbers in Section 1 of the field sheet.

**Section 1: Background Data**

| | | | |
|---|---|---|---|
| Subwatershed: | | Outfall ID: | |
| Today's date: | | Time (Military): | |
| Investigators: | | Form completed by: | |
| Temperature (°F): | Rainfall (in.): Last 24 hours: | Last 48 hours: | |
| Latitude: | Longitude: | GPS Unit: | GPS LMK #: |
| Camera: | | Photo #s: | |
| Land Use in Drainage Area (Check all that apply): | | | |
| ☐ Industrial | | ☐ Open Space | |
| ☐ Ultra-Urban Residential | | ☐ Institutional | |
| ☐ Suburban Residential | | Other: ____________ | |
| ☐ Commercial | | Known Industries: ____________ | |
| Notes (e.g.., origin of outfall, if known): | | | |

**Figure 23: Section 1 of the ORI Field Sheet**

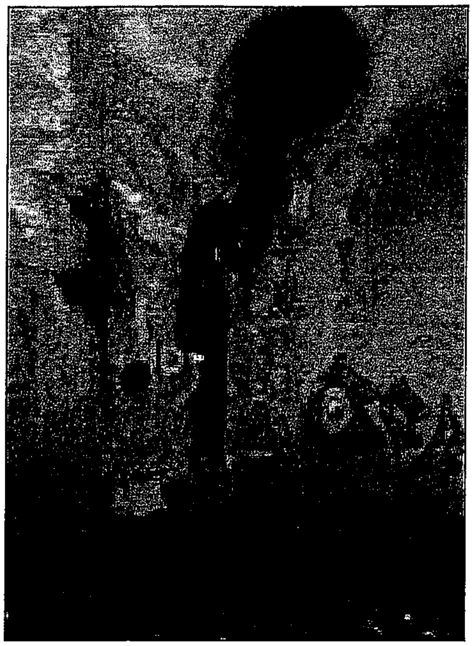


**Figure 24: Labeling an Outfall (a variety of outfall naming conventions can be used)**

The land use of the drainage area contributing to the outfall should also be recorded. This may not always be easy to characterize at large diameter outfalls that drain dozens or even hundreds of acres (unless you have aerial photographs). On the other hand, land use can be easily observed at smaller diameter outfalls, and in some cases, the specific origin can be found (e.g., a roof leader or a parking lot; Figure 25). The specific origin should be recorded in the "notes" portion of Section 1 on the field sheet.

## 11.5 ORI Section 2 - Outfall Description

This part of the ORI field sheet is where basic outfall characteristics are noted (Figure 26). These include material, and presence of flow at the outfall, as well as the pipe's dimensions (Figure 27). These measurements are used to confirm and supplement existing storm drain maps (if they are available). Many communities only map storm drain outfalls that exceed a given pipe diameter, and may not contain data on the material and condition of the pipe.

**Figure 25: The origin of this corrugated plastic pipe was determined to be a roof leader from the house up the hill.**

Section 2 of the field sheet also asks if the outfall is submerged in water or obstructed by sediment and the amount of flow, if present. Figure 28 provides some photos that illustrate how to characterize relative submergence, deposition and flow at outfalls. If no flow is observed at the outfall, you can skip the next two sections of the ORI field sheet and continue with Section 5.

**Section 2: Outfall Description**

| LOCATION | MATERIAL | | SHAPE | | DIMENSIONS (IN.) | SUBMERGED |
|---|---|---|---|---|---|---|
| ☐ Closed Pipe | ☐ RCP<br>☐ PVC<br>☐ Steel<br>☐ Other: ______ | ☐ CMP<br>☐ HDPE | ☐ Circular<br>☐ Eliptical<br>☐ Box<br>☐ Other | ☐ Single<br>☐ Double<br>☐ Triple<br>☐ Other: | Diameter/Dimensions:<br>______ | In Water:<br>☐ No<br>☐ Partially<br>☐ Fully<br>With Sediment:<br>☐ No<br>☐ Partially<br>☐ Fully |
| ☐ Open drainage | ☐ Concrete<br>☐ Earthen<br>☐ rip-rap<br>☐ Other: ____ | | ☐ Trapezoid<br>☐ Parabolic<br>☐ Other: | | Depth:<br>Top Width:<br>Bottom Width: | |
| ☐ In-Stream | (applicable when collecting samples) | | | | | |
| Flow Present? | ☐ Yes | ☐ No | *If No, Skip to Section 5* | | | |
| Flow Description (If present) | ☐ Trickle | ☐ Moderate | ☐ Substantial | | | |

**Figure 26: Section 2 of the ORI Field Sheet**

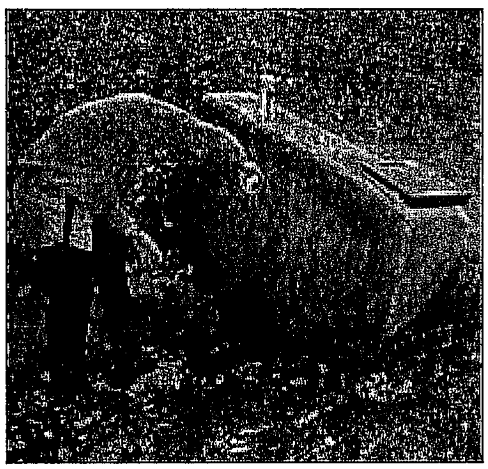
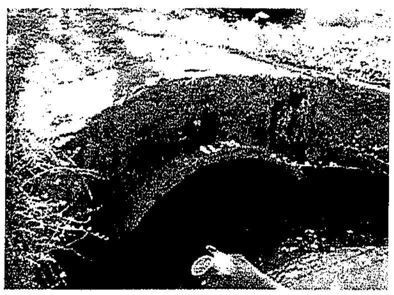
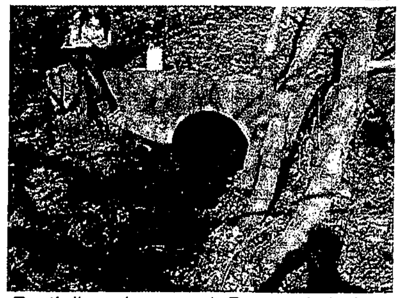


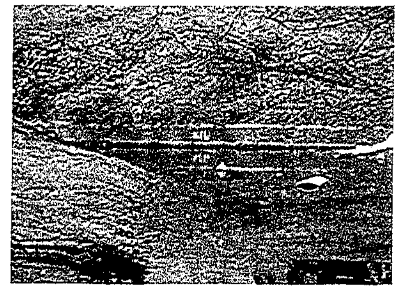
**Figure 27: Measuring Outfall Diameter**



Submerged: More than ½ below water



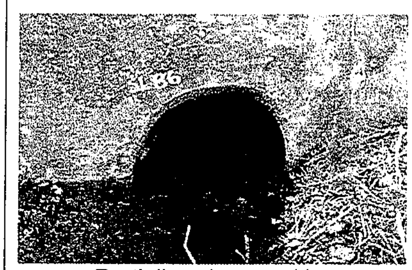
Partially submerged: Bottom is below water



Fully submerged: Can't see outfall

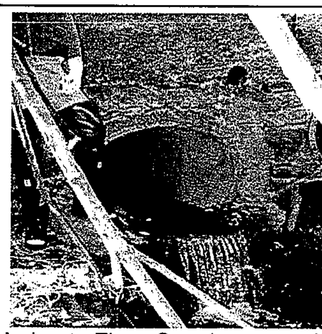
Outfall fully submerged by debris

Fully submerged from downstream trees trapping debris

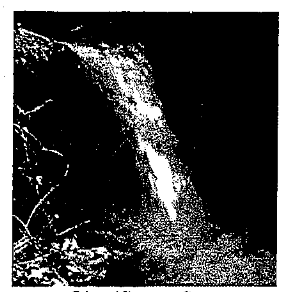


Partially submerged by leaf debris "back water"

Trickle Flow: Very narrow stream of water



Moderate Flow: Steady stream, but very shallow depth



Significant flow (Source is a fire hydrant discharge)

**Figure 28: Characterizing Submersion and Flow**

## 11.6 ORI Section 3 - Quantitative Characterization for Flowing Outfalls

This section of the ORI records direct measurements of **flowing outfalls**, such as flow, temperature, pH and ammonia (Figure 29). If desired, additional water quality parameters can be added to this section. Chapter 12 discusses the range of water quality parameters that can be used

**Section 3: Quantitative Characterization**

| FIELD DATA FOR FLOWING OUTFALLS | | | | |
|---|---|---|---|---|
| PARAMETER | | RESULT | UNIT | EQUIPMENT |
| ☐Flow #1 | Volume | | Liter | Bottle |
| | Time to fill | | Sec | |
| ☐Flow #2 | Flow depth | | In | Tape measure |
| | Flow width | ' " | Ft, In | Tape measure |
| | Measured length | ' " | Ft, In | Tape measure |
| | Time of travel | | S | Stop watch |
| Temperature | | | °F | Thermometer |
| pH | | | pH Units | Test strip/Probe |
| Ammonia | | | mg/L | Test strip |

**Figure 29: Section 3 of the ORI**

Field crews measure the rate of flow using one of two techniques. The first technique simply records the time it takes to fill a container of a known volume, such as a one liter sample bottle. In the second technique, the crew measures the velocity of flow, and multiplies it by the estimated cross sectional area of the flow.

To use the flow volume technique, it may be necessary to use a "homemade" container to capture flow, such as a cut out plastic milk container that is marked to show a one liter volume. The shape and flexibility of plastic containers allows crews to capture relatively flat and shallow flow (Figure 30). The flow volume is determined as the volume of flow captured in the container per unit time. The second technique measures flow rate based on velocity and cross sectional area, and is preferred for larger discharges where containers are too small to effectively capture the flow (Figure 31). The crew measures and marks off a fixed flow length (usually about five feet), crumbles leaves or other light material, and drops them into the discharge (crews can also carry peanuts or ping pong balls to use). The crew then measures the time it takes the marker to travel across the length. The velocity of flow is computed as the length of the flow path (in feet) divided by the travel time (in seconds). Next, the cross-sectional flow area is measured by taking multiple readings of the depth and width of flow. Lastly, cross-sectional area (in square feet) is multiplied by flow velocity (feet/second) to calculate the flow rate (in cubic feet/second).

Crews may also want to measure the quality of the discharge using relatively inexpensive probes and test strips (e.g., water temperature, pH, and ammonia). The choice of which indicator parameters to measure is usually governed by the overall IDDE monitoring framework developed by the community. Some communities have used probes or test strips to measure additional indicators such as conductivity, chlorine, and hardness. Research by Pitt (for this project) suggests that probes by Horiba for pH and conductivity are the most reliable and accurate, and that test strips have limited value.

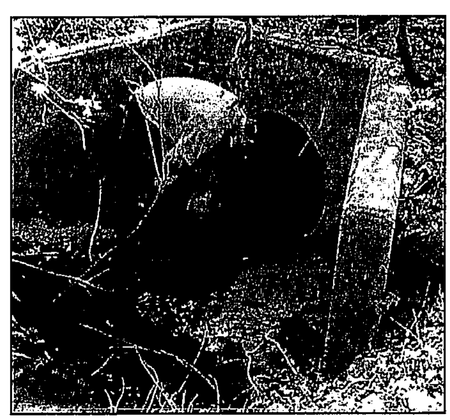


**Figure 30: Measuring flow as volume per time**

When probes or test strips are used, measurements should be made from a sample bottle that contains flow captured from the outfall. The exact measurement recorded by the field probe should be recorded in Section 3 of the field sheet. Some interpolation may be required for test strips, but do not interpolate further than the mid-range between two color points.

## 11.7 ORI Section 4 – Physical Indicators for Flowing Outfalls Only

This section of the ORI field sheet records data about four sensory indicators associated with **flowing outfalls** -- odor, color, turbidity and floatables (Figure 32). Sensory indicators can be detected by smell or sight, and require no measurement equipment. Sensory indicators do not always reliably predict illicit discharge, since the senses can be fooled, and may result in a "false negative" (i.e., sensory indicators fail to detect an illicit discharge when one is actually present). Sensory indicators are important, however, in detecting the most severe or obvious discharges. Section 4 of the field sheet asks whether the sensory indicator is present, and if so, what is its severity, on a scale of one to three.

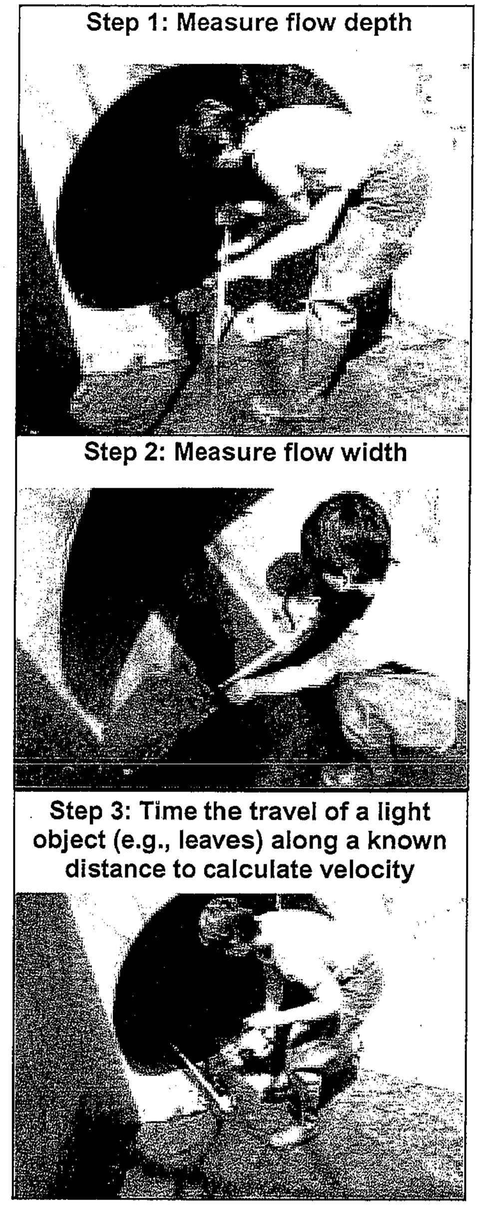



Figure 31: Measuring flow (as velocity times cross-sectional area)

**Section 4: Physical Indicators for Flowing Outfalls Only**
Are Any Physical Indicators Present in the flow? ☐ Yes ☐ No *(If No, Skip to Section 5)*

| INDICATOR | CHECK if Present | DESCRIPTION | RELATIVE SEVERITY INDEX (1-3) | | |
|---|---|---|---|---|---|
| Odor | ☐ | ☐ Sewage ☐ Rancid/sour ☐ Petroleum/gas ☐ Sulfide ☐ Other: | ☐ 1 – Faint | ☐ 2 – Easily detected | ☐ 3 – Noticeable from a distance |
| Color | ☐ | ☐ Clear ☐ Brown ☐ Gray ☐ Yellow ☐ Green ☐ Orange ☐ Red ☐ Other: | ☐ 1 – Faint colors in sample bottle | ☐ 2 – Clearly visible in sample bottle | ☐ 3 – Clearly visible in outfall flow |
| Turbidity | ☐ | See severity | ☐ 1 – Slight cloudiness | ☐ 2 – Cloudy | ☐ 3 – Opaque |
| Floatables -Does Not Include Trash!! | ☐ | ☐ Sewage (Toilet Paper, etc.) ☐ Suds ☐ Petroleum (oil sheen) ☐ Other: | ☐ 1 – Few/slight; origin not obvious | ☐ 2 – Some; indications of origin (e.g., possible suds or oil sheen) | ☐ 3 - Some; origin clear (e.g., obvious oil sheen, suds, or floating sanitary materials) |

Figure 32: Section 4 of the ORI Field Sheet

### *Odor*

Section 4 asks for a description of any odors that emanate from the outfall and an associated severity score. Since noses have different sensitivities, the entire field crew should reach consensus about whether an odor is present and how severe it is. A severity score of one means that the odor is faint or the crew cannot agree on its presence or origin. A score of two indicates a moderate odor within the pipe. A score of three is assigned if the odor is so strong that the crew smells it a considerable distance away from the outfall.

> **TIP**
> Make sure the origin of the odor is the outfall. Sometimes shrubs, trash or carrion, or even the spray paint used to mark the outfall can confuse the noses of field crews.

### *Color*

The color of the discharge, which can be clear, slightly tinted, or intense is recorded next. Color can be quantitatively analyzed in the lab, but the ORI only asks for a visual assessment of the discharge color and its intensity. The best way to measure color is to collect the discharge in a clear sample bottle and hold it up to the light (Figure 33). Field crews should also look for downstream plumes of color that appear to be associated with the outfall. Figure 34 illustrates the spectrum of colors that may be encountered during an ORI survey, and offers insight on how to rank the relative intensity or strength of discharge color. Color often helps identify industrial discharges; Appendix K provides guidance on colors often associated with specific industrial operations.

### *Turbidity*

The ORI asks for a visual estimate of the turbidity of the discharge, which is a measure of the cloudiness of the water. Like color, turbidity is best observed in a clear sample bottle, and can be quantitatively measured using field probes. Crews should also look for turbidity in the plunge pool below the outfall, and note any downstream turbidity plumes that appear to be related to the outfall. Field crews can sometimes confuse turbidity with color, which are related but are not the same. Remember, turbidity is a measure of how easily light can penetrate through the sample bottle, whereas color is defined by the tint or intensity of the color observed. Figure 34 provides some examples of how to distinguish turbidity from color, and how to rank its relative severity.

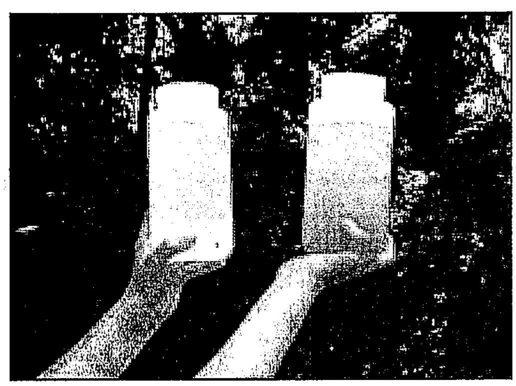
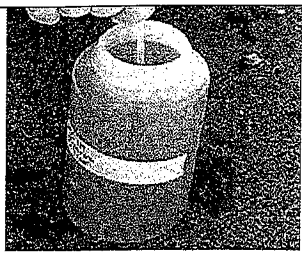


**Figure 33: Using a sample bottle to estimate color and turbidity**

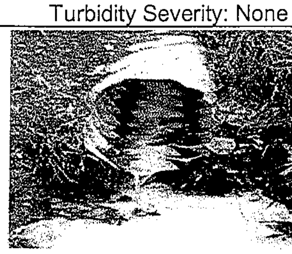


Color: Brown; Severity: 2
Turbidity Severity: 2

Chromium Spill
Color: Green; Severity: 3
Turbidity Severity: None

Highly Turbid Discharge
Color: Brown; Severity: 3
Turbidity Severity: 3

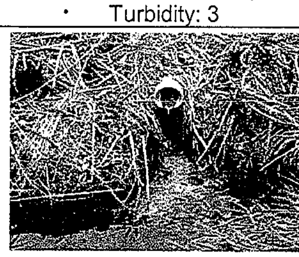
Sewage Discharge
Color: 3
Turbidity: 3



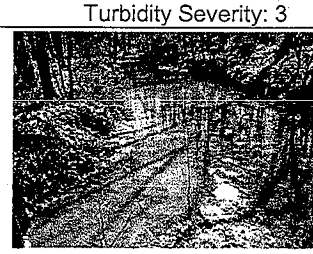
Paint
Color: White; Severity: 3
Turbidity: 3

Industrial Discharge
Color: Green; Severity: 3
Turbidity Severity: 3

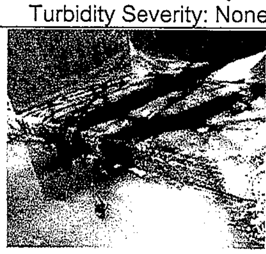
Blood
Color: Red; Severity: 3
Turbidity Severity: None



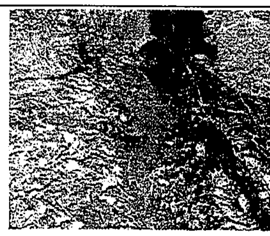
Failing Septic System:
Turbidity Severity: 3



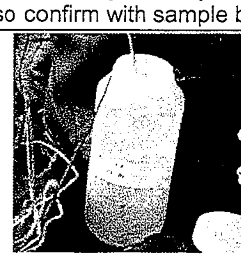
Turbidity in Downstream Plume
Turbidity Severity: 2
(also confirm with sample bottle)



High Turbidity in Pool
Turbidity Severity: 2
(Confirm with sample bottle)

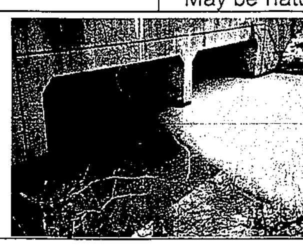


Iron Floc
Color: Reddish Orange; Severity: 3
(Often associated with a natural source)



Slight Turbidity
Turbidity: 1
(Difficult to interpret this observation; May be natural or an illicit discharge)

Construction Site Discharge
Turbidity Severity: 3



Discharge of Rinse from Floor Sanding (Found during wet weather)
Turbidity Severity: 3

**Figure 34: Interpreting Color and Turbidity**

## *Floatables*

The last sensory indicator is the presence of any floatable materials in the discharge or the plunge pool below. Sewage, oil sheen, and suds are all examples of floatable indicators; trash and debris are generally not in the context of the ORI. The presence of floatable materials is determined visually, and some guidelines for ranking their severity are provided in Figure 35, and described below.

If you think the floatable is sewage, you should automatically assign it a severity score of three since no other source looks quite like it. Surface oil sheens are ranked based on their thickness and coverage. In some cases, surface sheens may not be related to oil discharges, but instead are created by in-stream processes, such as shown in Figure 36. A thick or swirling sheen associated with a petroleum-like odor may be diagnostic of an oil discharge.

Suds are rated based on their foaminess and staying power. A severity score of three is designated for thick foam that travels many feet before breaking up. Suds that break up quickly may simply reflect water turbulence, and do not necessarily have an illicit origin. Indeed, some streams have naturally occurring foams due to the decay of organic matter. On the other hand, suds that are accompanied by a strong organic or sewage-like odor may indicate a sanitary sewer leak or connection. If the suds have a fragrant odor, they may indicate the presence of laundry water or similar wash waters.

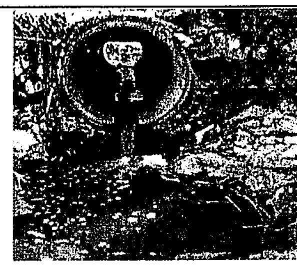
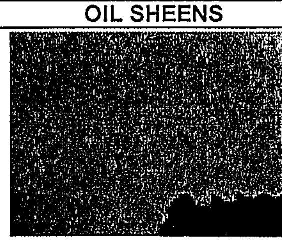
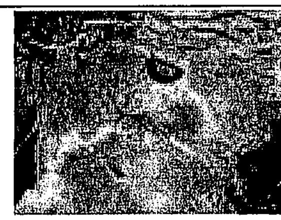
| | **SUDS** | |
|---|---|---|
|  Natural Foam<br>Note: Suds only associated with high flows at the "drop off"<br>Do not record. |  Low Severity Suds<br>Rating: 1<br>Note: Suds do not appear to travel; very thin foam layer |  High severity suds<br>Rating: 3<br>Sewage |
| | **OIL SHEENS** | |
|  Low Severity Oil Sheen<br>Rating: 1 |  Moderate Severity Oil Sheen<br>Rating: 2 |  High Severity Oil Film<br>Rating: 3 |

**Figure 35: Determining the Severity of Floatables**

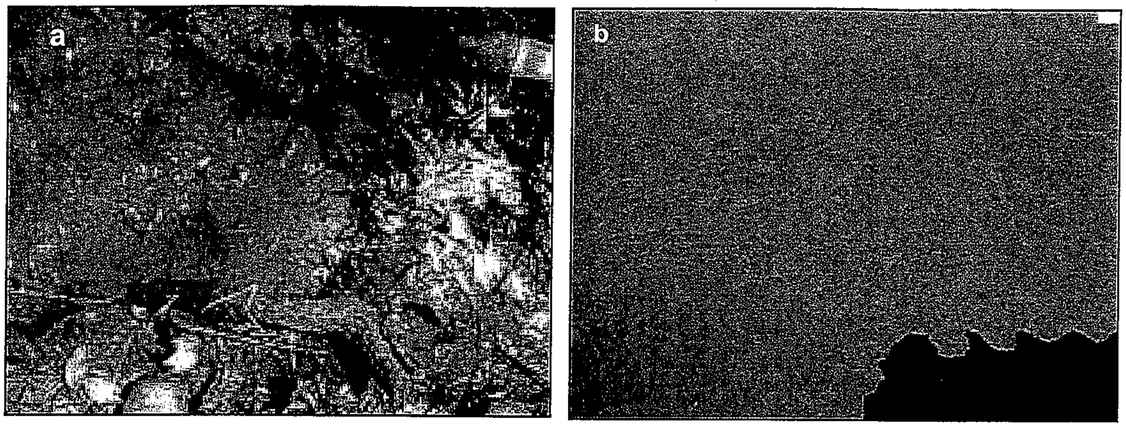



**Figure 36: Synthetic versus Natural Sheen (a) Sheen from bacteria such as iron floc forms a sheet-like film that cracks if disturbed (b) Synthetic oil forms a swirling pattern**

## 11.8 ORI Section 5 - Physical Indicators for Both Flowing and Non-Flowing Outfalls

Section 5 of the ORI field sheet examines physical indicators found at both **flowing and non-flowing** outfalls that can reveal the impact of past discharges (Figure 37). Physical indicators include outfall damage, outfall deposits or stains, abnormal vegetation growth, poor pool quality, and benthic growth on pipe surfaces. Common examples of physical indicators are portrayed in Figures 38 and 39. Many of these physical conditions can indicate that an intermittent or transitory discharge has occurred in the past, even if the pipe is not currently flowing. Physical indicators are not ranked according to their severity, because they are often subtle, difficult to interpret and could be caused by other sources. Still, physical indicators can provide strong clues about the discharge history of a storm water outfall, particularly if other discharge indicators accompany them.

**Section 5: Physical Indicators for Both Flowing and Non-Flowing Outfalls**
Are physical indicators that are not related to flow present? ☐ Yes ☐ No *(If No, Skip to Section 6)*

| INDICATOR | CHECK if Present | DESCRIPTION | COMMENTS |
|---|---|---|---|
| Outfall Damage | ☐ | ☐ Spalling, Cracking or Chipping ☐ Peeling Paint ☐ Corrosion | |
| Deposits/Stains | ☐ | ☐ Oily ☐ Flow Line ☐ Paint ☐ Other: | |
| Abnormal Vegetation | ☐ | ☐ Excessive ☐ Inhibited | |
| Poor pool quality | ☐ | ☐ Odors ☐ Colors ☐ Floatables ☐ Oil Sheen ☐ Suds ☐ Excessive Algae ☐ Other: | |
| Pipe benthic growth | ☐ | ☐ Brown ☐ Orange ☐ Green ☐ Other: | |

**Figure 37: Section 5 of the ORI Field Sheet**



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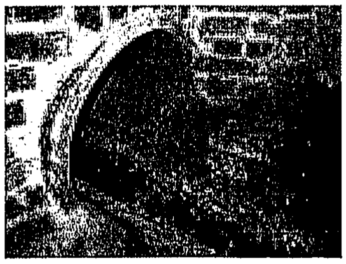
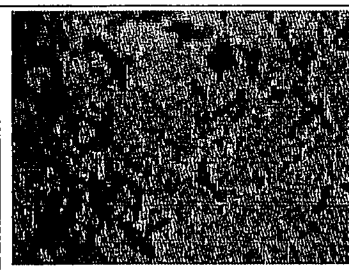

Bacterial growth at this outfall indicates nutrient enrichment and a likely sewage source.


This bright red bacterial growth often indicates high manganese and iron concentrations. Surprisingly, it is not typically associated with illicit discharges.


*Sporalitis* filamentous bacteria, also known as "sewage fungus" can be used to track down sanitary sewer leaks.


Algal mats on lakes indicate eutrophication. Several sources can cause this problem. Investigate potential illicit sources.


Illicit discharges or excessive nutrient application can lead to extreme algal growth on stream beds.

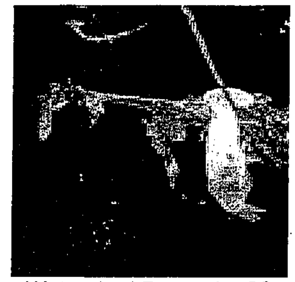

The drainage to this outfall most likely has a high nutrient concentration. The cause may be an illicit discharge, but may be excessive use of lawn chemicals.

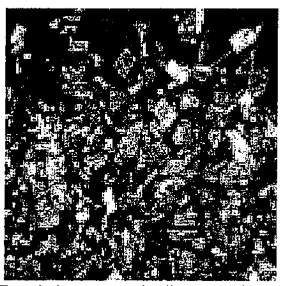

This brownish algae indicates an elevated nutrient level.

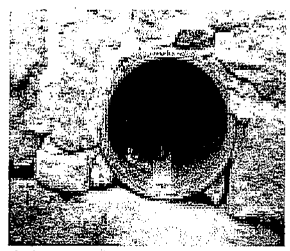
**Figure 38: Interpreting Benthic and Other Biotic Indicators**

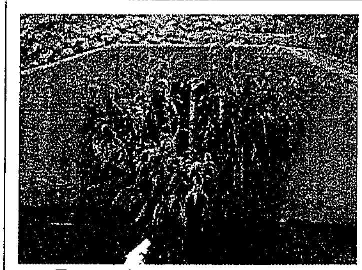

Reddish staining on the rocks below this outfall indicate high iron concentrations.

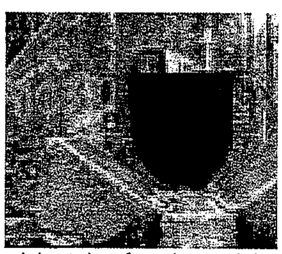

Toilet paper directly below the storm drain outlet.

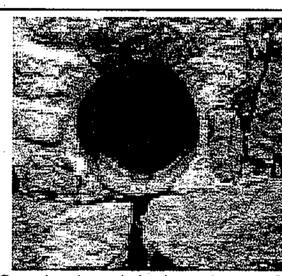

Watershed Protection??


Trash is not an indicator of illicit discharges, but should be noted.


Staining at the base of the outfall may indicate a persistent, intermittent discharge.


Excessive vegetation may indicate enriched flows associated with sewage.


Brownish stain of unclear origin. May be from degradation of the brick infrastructure.


Cracked rock below the outfall may indicate an intermittent discharge.

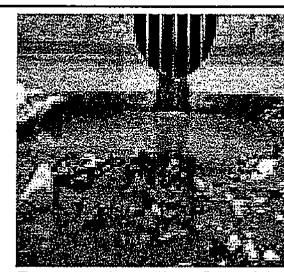

Poor pool quality. Consider sampling from the pool to determine origin.

**Figure 39: Typical Findings at both Flowing and Non-Flowing Outfalls**

## 11.9 ORI Sections 6-8 - Initial Outfall Designation and Actions

The last three sections of the ORI field sheet are where the crew designates the illicit discharge severity of the outfall and recommends appropriate management and monitoring actions (Figure 40). A discharge rating is designated as obvious, suspect, potential or unlikely, depending on the number and severity of discharge indicators checked in preceding sections.

It is important to understand that the ORI designation is only an initial determination of discharge potential. A more certain determination as to whether it actually is an illicit discharge is made using a more sophisticated indicator monitoring method. Nevertheless, the ORI outfall designation gives program managers a better understanding of the distribution and severity of illicit discharge problems within a subwatershed.

Section 7 of the ORI field sheet records whether indicator samples were collected for laboratory analysis, or whether an intermittent flow trap was installed (e.g., an optical brightener trap or caulk dam described in Chapter 13). Field crews should record whether the sample was taken from a pool or directly from the outfall, and the type of intermittent flow trap used, if any. This section can also be used to recommend follow-up sampling, if the crew does not carry sample bottles or traps during the survey.

The last section of the ORI field sheet is used to note any unusual conditions near the outfall such as dumping, pipe failure, bank erosion or maintenance needs. While these maintenance conditions are not directly related to illicit discharge detection, they often are of interest to other agencies and utilities that maintain infrastructure.

## 11.10 Customizing the ORI for a Community

The ORI method is meant to be adaptable, and should be modified to reflect local conditions and field experience. Some indicators can be dropped, added or modified in the ORI form. This section looks at four of the most common adaptations to the ORI:

- Open Channels
- Submerged/Tidally Influenced Outfalls
- Cold Climates
- Use of Biological Indicators

In each case, it may be desirable to revise the ORI field sheet to collect data reflecting these conditions.

### *Open Channels*

Field crews face special challenges in more rural communities that have extensive open channel drainage. The ditches and channels serve as the primary storm water conveyance system, and may lack storm drain and sewer pipes. The open channel network is often very long with only a few obvious outfalls that are located far apart. While the network can have illicit discharges from septic systems, they can typically only be detected in the ORI if a straight pipe is found. Some adaptations for open channel systems are suggested in Table 33.

**Section 6: Overall Outfall Characterization**

| | | | |
|---|---|---|---|
| ☐ Unlikely | ☐ Potential (presence of two or more indicators) | ☐ Suspect (one or more indicators with a severity of 3) | ☐ Obvious |

**Section 7: Data Collection**

| | | | |
|---|---|---|---|
| 1. Sample For The Lab? | ☐ Yes | ☐ No | |
| 2. If Yes, Collected From: | ☐ Flow | ☐ Pool | |
| 3. Intermittent flow trap set? | ☐ Yes | ☐ No | If Yes, type: ☐ OBM ☐ Caulk dam |

**Section 8: Any Non-Illicit Discharge Concerns (e.g., trash or needed infrastructure repairs)?**

**Figure 40: Sections 6-8 of the ORI Field Sheet**

### *Submerged/Tidally Influenced Outfalls*

The ORI can be problematic in coastal communities where outfalls are located along the waterfront and may be submerged at high tide. The ORI methods need to be significantly changed to address these constraints. Often, outfalls are initially located from offshore using canoes or boats, and then traced landward to the first manhole that is not tidally influenced. Field crews then access the storm drain pipe at the manhole and measure whatever indicators they can observe in the confined and dimly lit space. Table 33 recommends strategies to sample outfalls in the challenging environment of coastal communities.

### *Winter and Ice*

Ice can be used as a discharge indicator in northern regions when ice forms in streams and pipes during the winter months (Figure 41). Because ice lasts for many weeks, and most illicit discharges are warm, astute field crews can interpret outfall history from ice melting patterns along pipes and streams. For example, exaggerated melting at a frozen or flowing outfall may indicate warm water from sewage or industrial discharge. Be careful, because groundwater is warm enough to cause some melting at below freezing temperatures. Also, ice acts like an intermittent flow trap, and literally freezes these discharges. Crews should also look for these traps to find any discolored ice within the pipe or below the outfall.

A final winter indicator is "rime ice," which forms when steam freezes. This beautiful ice formation is actually a good indicator of sewage or other relatively hot discharge that causes steam to form (Figure 41).

### *Biological Indicators*

The diversity and pollution tolerance of various species of aquatic life are widely used as an indicator of overall stream health, and has sometimes been used to detect illicit discharges. One notable example is the presence of the red-eared slider turtle, which is used in Galveston, Texas to find sewage discharges, as they have a propensity for the nutrient rich waters associated with sewage (Figure 42).

**Table 33: Special Considerations for Open Channels/Submerged Outfalls**

| **OPEN CHANNELS** | |
|---|---|
| **Challenge** | **Suggested Modification** |
| Too many miles of channel to walk | Stop walking at a given channel size or drainage area |
| Difficulty marking them | Mark on concrete or adjacent to earth channel |
| Interpreting physical indicators | For open channels with mild physical indicators, progress up the system to investigate further. |
| **SUBMERGED/TIDALLY INFLUENCED OUTFALLS** | |
| **Challenge** | **Suggested Modification** |
| Access for ORI – Tidal Influence | Access during low tide |
| Access for ORI – Always submerged | Access by boat or by shore walking |
| Interpreting physical indicators | For outfalls with mild physical indicators, also inspect from the nearest manhole that is not influenced by tides |
| Sampling (if necessary) | Sample "up pipe" |

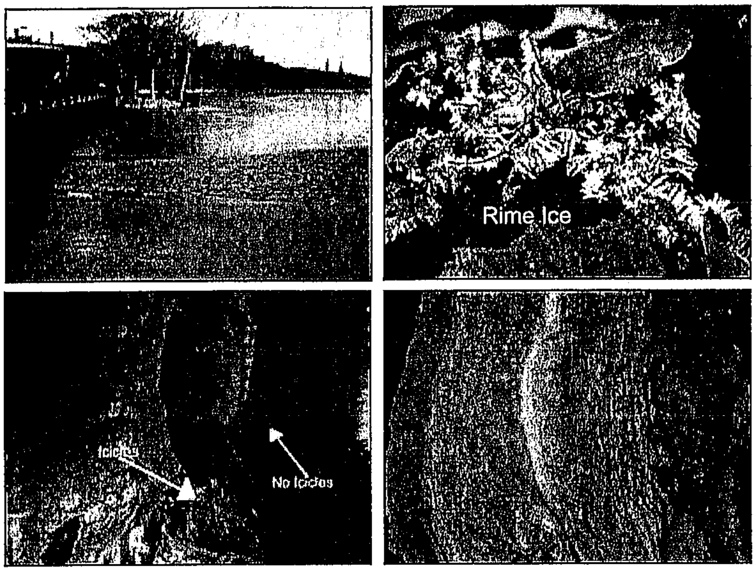



Figure 41: Cold climate indicators of illicit discharges

Figure 42: One biological indicator is this red-eared slider turtle

## 11.11 Interpreting ORI Data

The ORI generates a wealth of information that can provide managers with valuable insights about their illicit discharge problems, if the data are managed and analyzed effectively. The ORI can quickly define whether problems are clustered in a particular area or spread across the community. This section presents a series of methods to compile, organize and interpret ORI data, including:

1. Basic Data Management and Quality Control
2. Outfall Classification
3. Simple Suspect Outfall Counts
4. Mapping ORI Data
5. Subwatershed and Reach Screening
6. Characterizing IDDE Problems at the Community Level

The level of detail for each analysis method should be calibrated to local resources, program goals, and the actual discharge problems discovered in the stream corridor. In general, the most common conditions and problems will shape your initial monitoring strategy, which prioritizes the subwatersheds or reaches that will be targeted for more intensive investigations.

Program managers should analyze ORI data well before every stream mile is walked in the community, and use initial results to modify field methods. For example, if initial results reveal widespread potential problems, program managers may want to add more indicator monitoring to the ORI to track down individual discharge sources (see Chapter 12). Alternatively, if the same kind of discharge problem is repeatedly found, it may be wise to investigate whether there is a common source or activity generating it (e.g., high turbidity observed at many flowing outfalls as a result of equipment washing at active construction sites).

### Basic Data Management and Quality Control

The ORI produces an enormous amount of raw data to characterize outfall conditions. It is not uncommon to compile dozens of individual ORI forms in a single subwatershed. The challenge is to devise a system to organize, process, and translate this data into simpler outputs and formats that can guide illicit discharge elimination efforts. The system starts with effective quality control procedures in the field.

Field sheets should be managed using either a three-ring binder or a clipboard. A small field binder offers the ability to quickly flip back and forth among the outfall forms. Authorization letters, emergency contact lists, and extra forms can also be tucked inside.

At the end of each day, field crews should regroup at a predetermined location to compare notes. The crew leader should confirm that all survey reaches and outfalls of interest have been surveyed, discuss initial findings, and deal with any logistical problems. This is also a good time to check whether field crews are measuring and recording outfall data in the same way, and are consistent in what they are (or are not) recording. Crew leaders should also use this time to review field forms for accuracy and thoroughness. Illegible handwriting should be neatened and details added to notes and any sketches. The crew leader should also organize the forms together into a single master binder or folder for future analysis.

Once crews return from the field, data should be entered into a spreadsheet or database. A Microsoft Access database is provided with this Manual as part of Appendix D (Figure 43), and is supplied on a compact disc with each hard copy. It can also be downloaded with Appendix D from http://www.stormwatercenter.net. Information stored in this database can easily be imported into a GIS for mapping purposes. The GIS can generate its own database table that allows the user to create subwatershed maps showing outfall characteristics and problem areas.

Once data entry is complete, be sure to check the quality of the data. This can be done quickly by randomly spot-checking 10% of the entered data. For example, if 50 field sheets were completed, check five of the spreadsheet or database entries. When transferring data into GIS, quality control maps that display labeled problem outfalls should be created. Each survey crew is responsible for reviewing the accuracy of these maps.

### Outfall Classification

A simple outfall designation system has been developed to summarize the discharge potential for individual ORI field sheets. Table 34 presents the four outfall designations that can be made.

**Table 34: Outfall Designation System Using ORI Data**

| Designation | Description |
|---|---|
| **1:** Obvious Discharge | Outfalls where there is an illicit discharge that doesn't even require sample collection for confirmation |
| **2:** Suspect Discharge | Flowing outfalls with high severity on one or more physical indicators |
| **3:** Potential Discharge | Flowing or non-flowing outfalls with presence of two or more physical indicators |
| **4:** Unlikely Discharge | Non-flowing outfalls with no physical indicators of an illicit discharge |



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### Simple Suspect Outfall Counts

The first priority is to count the frequency of each outfall designation in the subwatershed or the community as a whole. This simple screening analysis counts the number of problem outfalls per stream mile (i.e., the sum of outfalls designated as having potential, suspected or obvious illicit discharge potential). The density of problem outfalls per stream mile is an important metric to target and screen subwatersheds.

Based on problem outfall counts, program managers may discover that a particular monitoring strategy may not apply to the community. For example, if few problem outfalls are found, an extensive follow-up monitoring program may not be needed, so that program resources can be shifted to pollution hotlines to report and control transitory discharges such as illegal dumping. The key point of this method is to avoid getting lost in the raw data, but look instead to find patterns that can shape a cost-effective IDDE program.

### Mapping ORI Data

Maps are an excellent way to portray outfall data. If a GIS system is linked to the ORI database, maps that show the spatial distribution of problem outfalls, locations of dumping, and overall reach conditions can be easily generated. Moreover, GIS provides flexibility that allows for rapid updates to maps as new data are collected and compiled. The sophistication and detail of maps will depend on the initial findings, program goals, available software, and GIS capability.

Subwatershed maps are also an effective and important communication and education tool to engage stakeholders (e.g., public officials, businesses and community residents), as they can visually depict reach quality and the location of problem outfalls. The key point to remember is that maps are tools for understanding data. Try to map with a purpose in mind. A large number of cluttered maps may only confuse, while a smaller number with select data may stimulate ideas for the follow-up monitoring strategy.

### Subwatershed and Survey Reach Screening

Problem outfall metrics are particularly valuable to screen or rank priority subwatersheds or survey reaches. The basic approach is simple: select the outfall metrics that are most important to IDDE program goals, and then see how individual subwatersheds or reaches rank in the process. This screening process can help determine which subwatersheds will be priorities for initial follow-up monitoring efforts. When feasible, the screening process should incorporate non-ORI data, such as existing dry weather water quality data, citizen complaints, permitted facilities, and habitat or biological stream indicators.

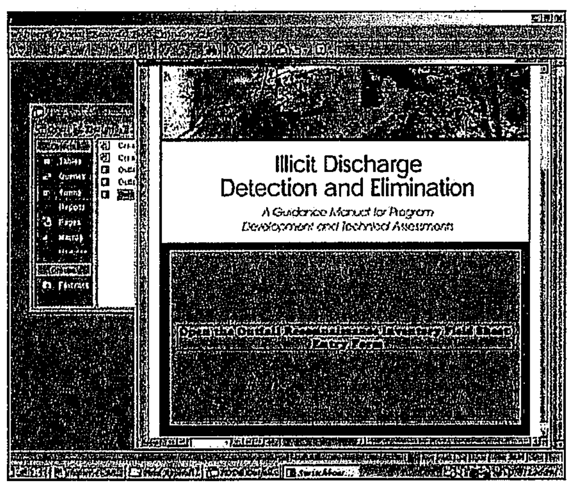


**Figure 43: Sample screen from ORI Microsoft Access database**



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An example of how outfall metrics can screen subwatersheds is provided in Table 35. In this hypothetical example, four metrics were used to screen three subwatersheds within a community: number of suspect discharges, subwatershed population as a percent of the total community, number of industrial discharge permits, and number of outfalls per stream mile. Given these screening criteria, subwatershed C was selected for the next phase of detailed investigation.

### Characterizing the IDDE Problem at the Community Level

ORI data should be used to continuously revisit and revise the IDDE program as more is learned about the nature and distribution of illicit discharge problems in the community. For example, ORI discharge designation should be compared against illicit discharge potential (IDP) predictions made during the original desktop analysis (Chapter 5) to refine discharge screening factors, and formulate new monitoring strategies.

In general, community illicit discharge problem can be characterized as minimal, clustered, or severe (Table 36). In the minimal scenario, very few and scattered problems exist; in the clustered scenario, problems are located in isolated subwatersheds; and in the severe scenario, problems are widespread.

**Table 35: An Example of ORI Data Being Used to Compare Across Subwatersheds**

| | # of suspect discharges | Population as % of total community | # of industrial discharge permits | # of outfalls per stream/ conveyance mile |
|---|---|---|---|---|
| Subwatershed A | 2 | 30 | 4 | 6 |
| Subwatershed B | 1 | 10 | 0 | 3 |
| Subwatershed C | 8 | 60 | 2 | 12 |

**Table 36: Using Stream and ORI Data to Categorize IDDE Problems**

| Extent | ORI Support Data |
|---|---|
| **Minimal** | • Less than 10% of total outfalls are flowing<br>• Less than 20% of total outfalls with obvious, suspect or potential designation |
| **Clustered** | • Two thirds of the flowing outfalls are located within one third of the subwatersheds<br>• More than 20% of the communities subwatersheds have greater than 20% of outfalls with obvious, suspect or potential designation |
| **Severe** | • More than 10% of total outfalls are flowing<br>• More than 50% of total outfalls with obvious, suspect or potential designation<br>• More than 20% of total outfalls with obvious or suspect designation |

## 11.12 Budgeting and Scoping the ORI

Many different factors come into play when budgeting and scoping an ORI survey: equipment needs, crew size and the stream miles that must be covered. This section presents some simple rules of thumb for ORI budgeting.

Equipment costs for the ORI are relatively minor, with basic equipment to outfit one team of three people totaling about $800 (Table 37). This cost includes one-time expenses to acquire waders, a digital camera and a GPS unit, as well as disposable supplies.

The majority of the budget for an ORI is for staffing the desktop analysis, field crews and data analysis. Field crews can consist of two or three members, and cover about two to three miles of stream (or open channel) per day. Three staff-days should be allocated for pre- and post-field work for each day spent in the field.

Table 38 presents example costs for two hypothetical communities that conduct the ORI. Community A has 10 miles of open channel to investigate, while Community B has 20 miles. In addition, Community A has fewer staff resources available and therefore uses two-person field crews, while Community B uses three-person field crews. Total costs are presented as annual costs, assuming that each community is able to conduct the ORI for all miles in one year.

**Table 37: Typical Field Equipment Costs for the ORI**

| Item | Cost |
|---|---|
| 100 Latex Disposable Gloves | $ 25 |
| 5 Wide Mouth Sample Bottles (1 Liter) | $ 20 |
| Large Cooler | $ 25 |
| 3 Pairs of Waders | $ 150 |
| Digital Camera | $ 200 |
| 20 Cans of Spray Paint | $ 50 |
| Test Kits or Probes | $ 100-$500 |
| 1 GPS Unit | $ 150 |
| 1 Measuring Tape | $ 10 |
| 1 First Aid Kit | $ 30 |
| Flashlights, Batteries, Labeling tape, Clipboards | $ 25 |
| **Total** | **$ 785-$1185** |

**Table 38: Example ORI Costs**

| Item | Community A | Community B |
|---|---|---|
| Field Equipment[1] | $700 | $785 |
| Staff Field Time[2] | $2,000 | $6,000 |
| Staff Office Time[3] | $3,000 | $6,000 |
| **Total** | **$5,700** | **$12,785** |

[1] *From Table 44*
[2] *Assumes $25/hour salary (2 person teams in Community A and three- person teams in Community B) and two miles of stream per day.*
[3] *Assumes three staff days for each day in field.*

# Chapter 12: Indicator Monitoring

Indicator monitoring is used to confirm illicit discharges, and provide clues about their source or origin. In addition, indicator monitoring can measure improvements in water quality during dry weather flow as a result of the local IDDE program. This chapter reviews the suite of chemical indicator parameters that can identify illicit discharges, and provides guidance on how to collect, analyze and interpret each parameter.

Program managers have a wide range of indicator parameters and analytical methods to choose from when determining the presence and source of illicit discharges. The exact combination of indicator parameters and methods selected for a community is often unique. This chapter recommends some general approaches for communities that are just starting an indicator monitoring program or are looking for simple, cost-effective, and safe alternatives to their current program.

## *Organization of the Chapter*

This chapter provides technical support to implement the basic IDDE monitoring framework shown in Figure 44, and is organized into eight sections as follows:

1. Review of indicator parameters
2. Sample collection considerations
3. Methods to analyze samples
4. Methods to distinguish flow types
5. Chemical library
6. Special monitoring methods for intermittent and transitory discharges
7. In-stream dry weather monitoring
8. Costs for indicator monitoring

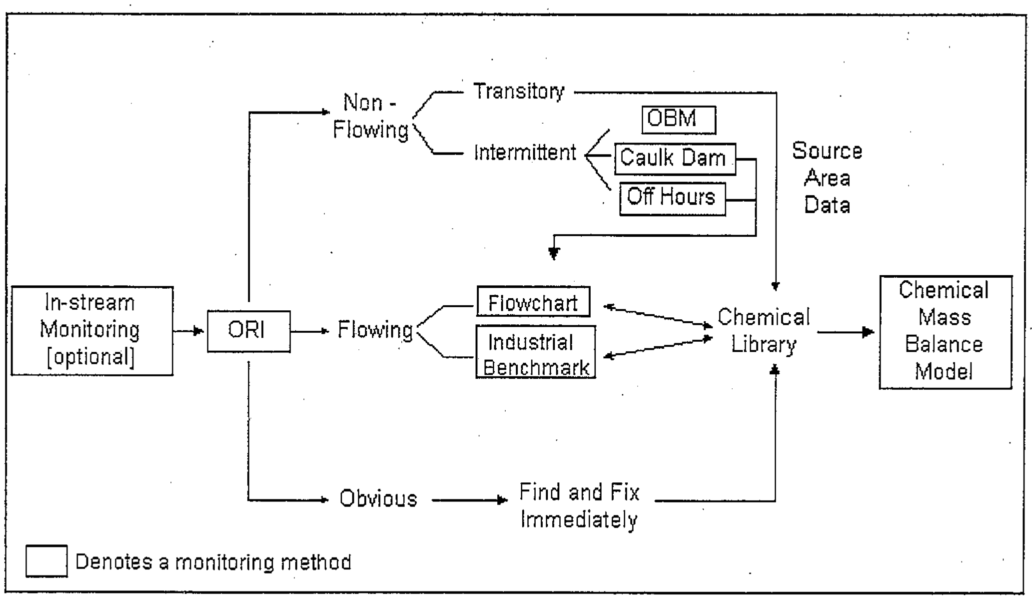


**Figure 44: IDDE Monitoring Framework**



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Program managers developing an indicator monitoring program need a solid background in basic water chemistry, and field and laboratory methods. This chapter describes the major factors to consider when designing an indicator monitoring program for illicit discharges, and assumes some familiarity with water quality sampling and analysis protocols.

Indicator monitoring terminology can be confusing, so some of the basic terms are defined as they specifically relate to illicit discharge control. Some of the common terms introduced in this Chapter are defined below:

*Chemical Library:* A database and statistical summary of the chemical characteristics, or "fingerprint" of various discharge flow types in a community (e.g., sewage, wash water, shallow groundwater, tap water, irrigation water, and liquid wastes). The library is assembled by collecting and analyzing representative samples from the source of each major flow type in the community.

*Chemical Mass Balance Model (CMBM)*: A computer model that uses flow characteristics from a chemical library file of flow types to estimate the most likely source components that contribute to dry weather flows.

*Detergents:* Commercial or retail products used to wash clothing. Presence of detergents in flow is usually measured as surfactants or fluorescence.

*False Negative:* An indicator sample that identifies a discharge as uncontaminated when it actually is contaminated.

*False Positive:* An indicator sample that identifies a discharge as contaminated when it is not.

*Flow Chart Method*: The use of four indicators (surfactants, ammonia, potassium, and fluoride) to identify illicit discharges.

*Indicator Parameter:* A water quality measurement that can be used to identify a specific discharge flow type, or discriminate between different flow types.

*Monitoring:* A strategy of sample collection and laboratory analysis to detect and characterize illicit discharges.

*Optical Brightener Monitoring (OBM) Traps:* Traps that use absorbent pads to capture dry weather flows, which can later be observed under a fluorescent light to determine if detergents using optical brighteners were present.

*Reagent:* A chemical added to a sample to create a reaction that enables the measurement of a target chemical parameter.

*Sampling:* Water sample collection from an outfall, pipe or stream, along with techniques to store and preserve them for subsequent laboratory analysis.

*Surfactants:* The main component of commercial detergents that detaches dirt from the clothing. The actual concentration of surfactants is much lower than the concentration of detergent, but analytical methods that measure surfactants are often referred to as "detergents." To avoid confusion, this chapter expresses the concentration of surfactants as "detergents as surfactants."

## 12.1 Indicator Parameters to Identify Illicit Discharges

At least fifteen different indicator parameters can confirm the presence or origin of an illicit discharge. These parameters are discussed in detail in Appendix F and include:

- Ammonia
- Boron
- Chlorine
- Color
- Conductivity
- Detergents
- *E. coli*, enterococi, and total coliform
- Fluorescence
- Fluoride
- Hardness
- pH
- Potassium
- Surface Tension
- Surfactants
- Turbidity

In most cases, however, only a small subset of indicator parameters (e.g., three to five) is required to adequately characterize an illicit discharge. This section summarizes the different indicator parameters that have been used.

An ideal indicator parameter should reliably distinguish illicit discharges from clean water and provide clues about its sources. In addition, they should have the following characteristics:

- Have a significantly different concentration for major flow or discharge types
- Exhibit relatively small variations in concentrations within the same flow or discharge type
- Be conservative (i.e., concentration will not change over time due to physical, chemical or biological processes)
- Be easily measured with acceptable detection limits, accuracy, safety and repeatability.

No single indicator parameter is perfect, and each community must choose the combination of indicators that works best for their local conditions and discharge types. Table 39 summarizes the parameters that meet most of the indicator criteria, compares their ability to detect different flow types, and reviews some of the challenges that may be encountered when measuring them. More details on indicator parameters are provided in Appendix F.

Data in Table 39 are based on research by Pitt (Appendix E) conducted in Alabama, and therefore, the percentages shown to distinguish "hits" for specific flow types should be viewed as representative and may shift for each community. Also, in some instances, indicator parameters were "downgraded" to account for regional variation or dilution effects. For example, both color and turbidity are excellent indicators of sewage based on discharge fingerprint data, but both can vary regionally depending on the composition of clean groundwater.

| Table 39: Indicator Parameters Used to Detect Illicit Discharges | | | | | |
|---|---|---|---|---|---|
| Parameter | Discharge Types it can Detect | | | | Laboratory/Analytical Challenges |
| | Sewage | Washwater | Tap Water | Industrial or Commercial Liquid Wastes | |
| Ammonia | ● | ⦿ | ○ | ⦿ | Can change into other nitrogen forms as the flow travels to the outfall |
| Boron | ⦿ | ⦿ | ○ | N/A | |
| Chlorine | ○ | ○ | ○ | ⦿ | High chlorine demand in natural waters limits utility to flows with very high chlorine concentrations |
| Color | ⦿ | ⦿ | ○ | ⦿ | |
| Conductivity | ⦿ | ⦿ | ○ | ⦿ | Ineffective in saline waters |
| Detergents – Surfactants | ● | ● | ○ | ⦿ | Reagent is a hazardous waste |
| *E. coli*<br>Enterococci<br>Total Coliform | ⦿ | ○ | ○ | ○ | 24-hour wait for results<br>Need to modify standard monitoring protocols to measure high bacteria concentrations |
| Fluoride* | ○ | ○ | ● | ⦿ | Reagent is a hazardous waste<br>Exception for communities that do not fluoridate their tap water |
| Hardness | ⦿ | ⦿ | ⦿ | ⦿ | |
| pH | ○ | ⦿ | ○ | ⦿ | |
| Potassium | ⦿ | ○ | ○ | ● | May need to use two separate analytical techniques, depending on the concentration |
| Turbidity | ⦿ | ⦿ | ○ | ⦿ | |

● Can almost always (>80% of samples) distinguish this discharge from clean flow types (e.g., tap water or natural water). For tap water, can distinguish from natural water.
⦿ Can sometimes (>50% of samples) distinguish this discharge from clean flow types depending on regional characteristics, or can be helpful in combination with another parameter
○ Poor indicator. Cannot reliably detect illicit discharges, or cannot detect tap water
N/A: Data are not available to assess the utility of this parameter for this purpose.
Data sources: Pitt (this study)
*Fluoride is a poor indicator when used as a single parameter, but when combined with additional parameters (such as detergents, ammonia and potassium), it can almost always distinguish between sewage and washwater.

## 12.2 Sample Collection Considerations

Sample collection is an important aspect of an IDDE program. Program managers need to be well informed about the key facets of sampling such as sample handling, QA/QC, and safety. The guidance in this section is limited to an overview of sample collection considerations including: equipment needed for collecting samples, elements of sampling protocols, and general tips. Several useful documents are available that detail accepted water quality sampling protocols such as the following:

- Burton and Pitt (2002) - Stormwater Effects Handbook: A Toolbox for Watershed Managers, Scientists, and Engineers

- USGS National Field Manual for the Collection of Water-Quality Data http://water.usgs.gov/owq/FieldManual/
- *Standard Methods for the Examination of Water and Wastewater* http://www.standardmethods.org/
- *EPA NPDES Stormwater Sampling Guidance Document* *http://cfpub.epa.gov/npdes* (Note: while this document is oriented towards wet weather sampling, there are still many sampling procedures that apply to dry weather sampling)

State environmental agencies are also a good resource to contact for recommended or required sampling protocols.

### *Equipment Needed for Field Sampling*

The basic equipment needed to collect samples is presented in Table 40. Most sampling equipment is easily available for purchase from scientific supply companies and various retail stores.

### *Developing a Consistent Sample Collection Protocol*

Samples should never be collected haphazardly. To get reliable, accurate, and defensible data, it is important to develop a consistent field sampling protocol to collect each indicator sample. A good field sampling protocol incorporates eight basic elements:

1. Where to collect samples
2. When to collect samples
3. Sample bottle preparation
4. Sample collection technique
5. Storage and preservation of samples
6. Sample labeling and chain of custody plan
7. Quality assurance/control samples
8. Safety considerations

Appendix G provides more detail on each monitoring element. Some communities already have established sampling protocols that are used for in-stream or wet weather sampling. In most cases these existing sampling protocols are sufficient to conduct illicit discharge sampling.

### *Tips for Collecting Illicit Discharge Samples*

The following tips can improve the quality of your indicator monitoring program.

1. Remember to fill out an ORI field form at every outfall where samples are collected. The ORI form documents sample conditions, outfall characteristics and greatly aids in interpreting indicator monitoring data.

2. Most state water quality agencies have detailed guidance on sampling protocols. These resources should be consulted and the appropriate guidelines followed. Another useful guidance on developing a quality assurance plan is the "Volunteer Monitor's Guide to Quality Assurance Project Plans" (EPA, 1996).

| **Table 40: Equipment Needed for Sample Collection** |
|---|
| • A cooler (to be kept in the vehicle)<br>• Ice or "blue ice" (to be kept in the vehicle)<br>• Permanent marker (for labeling the samples)<br>• Labeling tape or pre-printed labels<br>• Several dozen one-liter polyethylene plastic sample bottles<br>• A "dipper," a measuring cup at the end of a long pole, to collect samples from outfalls that are hard to reach<br>• Bacteria analysis sample bottles (if applicable), typically pre-cleaned 120mL sample bottles, to ensure against contamination |

3. Sample in batches where feasible to cut down on field and mobilization time.

4. Avoid sampling lagged storm water flows by sampling at least 48 to 72 hours after runoff producing events.

5. It may be necessary to collect multiple samples at a single outfall if preservatives are going to be used. Preservatives are typically necessary when long hold times are required for samples before analysis occurs. Appendix G contains guidance on the required preservation and maximum allowable hold times for various parameters.

## 12.3 Methods to Analyze Indicator Samples

This section reviews methods to analyze indicator samples, and begins with a discussion of whether they should be analyzed in-house or sent to an independent contract lab. Next, recommended methods for analyzing indicator parameters are outlined, along with data on their comparative cost, safety, and accuracy. Lastly, tips are offered to improve an indicator monitoring program.

### *Analyzing Samples In-house vs. Contract Lab*

Program managers need to decide whether to analyze samples in-house, or through an independent monitoring laboratory. The decision on which route to take is often based on the answers to the following questions:

- *What level of precision or accuracy is needed for the indicator parameter(s)?* Precise and accurate data are needed when indicator monitoring is used to legally document a violation or enforcement action. The lab setting is important, since the quality of the data may be challenged. Precise data are also needed for outfalls that have very large drainage areas. These discharges are often diluted by groundwater, so lab methods must be sensitive and have low detection limits to isolate illicit discharges that are masked or blended with other flow types. Accurate data are also needed for large outfalls since the cost and effort triggered by a false positive reading to track and isolate discharges in a large and complex drainage area is much greater.

- *How quickly are sampling results needed?* Fast results are essential if the community wants to respond instantly to problem outfalls. In this case, the capability to collect and analyze indicator samples in-house is desirable to provide quick response.

- *How much staff time and training is needed to support in-house analysis?* Local staff that perform lab analysis must be certified in laboratory safety, quality control and proper analytical procedures. Communities that do not expect to collect many indicator samples may want to utilize a contract lab to reduce staff training costs.

- *Does a safe environment exist to analyze samples and dispose of wastes?* A safe environment is needed for lab analysis including storage in a fireproof environment, eyewash stations, safety showers, fume hoods and ventilation. Lab workers should have standard safety equipment such as gloves, safety glasses and lab coats. Lastly, many of the recommended analytical methods create small quantities of hazardous wastes that need to be properly disposed. Program managers should carefully evaluate in-house work space to determine if a safe lab environment can be created.

- *What is the comparative cost for sample analysis in each option?* The initial up-front costs to use an independent laboratory are normally lower than those required to establish an in-house analysis capability. An in-house analysis capability normally becomes cost-effective when a community expects to analyze more than 100 indicator samples per year. Section 12.8 outlines some of the key budget factors to consider when making this decision, but program managers should always get bids from reputable and certified contract labs to determine analysis costs.

- *Are existing monitoring laboratories available in the community?* Cost savings are often realized if an existing wastewater treatment or drinking water lab can handle the sample analysis. These labs normally possess the equipment, instruments and trained staff to perform the water quality analyses for indicator parameters.

### Considerations for In-house Analysis Capability

Three basic settings can be used to analyze indicator parameters in-house: direct field measurements, small office lab, and a more formal municipal lab. The choice of which in-house setting to use depends on the indicator parameters selected, the need for fast and accurate results and safety/disposal considerations.

*In-Field Analysis* – A few indicator parameters can be analyzed in the field with probes and other test equipment (Figure 45). While most field parameters can identify problem outfalls, they generally cannot distinguish the specific type of discharge. Some of the situations where in-field analysis[10] is best applied are:

- When a community elects to use one or two indicator parameters, such as ammonia and potassium, that can be measured fairly easily in the field

- When field crews measure indicator parameters to trace or isolate a discharge in a large storm drain pipe network, and need quick results to decide where to go next

*Office Analysis* – Many of the recommended indicator parameters can be analyzed in an informal "office" lab with the possible exception of surfactants and fluoride (Figure 46). The office analysis option makes sense in communities that have available and trained staff, and choose analytical methods that are safe and have few hazardous waste disposal issues. Another option is to use the office lab to conduct most indicator analyses, but send out fluoride and surfactant indicator samples to a contract lab.

**TIP**
The methodology for any bacteria analysis also has a waste disposal issue (e.g., biohazard). Check state guidance for appropriate disposal procedures.

[10] Some communities have had success with in-field analysis; however, it can be a challenging environment to conduct rapid and controlled chemical analysis. Therefore, it is generally recommended that the majority of analyses be conducted in a more controlled "lab" setting.

*Formal Laboratory Setting* – The ideal option in many communities is to use an existing municipal or university laboratory. Existing labs normally have systems in place to dispose of hazardous material, have room and facilities for storing samples, and are equipped with worker safety features. Be careful to craft a schedule that does not interfere with other lab activities.

When in-house analysis is used, program managers need to understand the basic analytical options, safety considerations, equipment needs and analysis costs for each analytical method used to measure indicator parameters. This understanding helps program managers choose what indicator parameters to collect and where they should be analyzed. Much of this information is detailed in Appendix F and summarized below.

## Supplies and Equipment

The basic supplies needed to perform lab analysis are described in Table 41, and are available from several scientific equipment suppliers. In addition, reagents, disposable supplies and some specialized instruments may be needed, depending on the specific indicator parameters analyzed. For a partial list of suppliers, consult the Volunteer Stream Monitoring Manual (US EPA, 1997), which can be accessed at www.epa.gov/owow/monitoring/volunteer/stream/appendb.html. Table 42 summarizes the equipment needed for each analytical method.

**Figure 45: Analyzing samples in the back of a truck.**

**Figure 46: Office/lab set up in Fort Worth, TX**

| Table 41: Basic Lab Supplies | |
|---|---|
| Disposable Supplies<br>• Deionized water (start with about 10 gallons, unless a reverse osmosis machine is available)<br>• Nitric acid for acid wash (one or two gallons to start)<br>Safety<br>• Lab or surgical gloves<br>• Lab coats<br>• Safety glasses | Glassware/Tools<br>• About two dozen each of 100 and 200 mL beakers<br>• Two or three 100 mL graduated cylinders<br>• Two or three tweezers<br>• Pipettes to transfer samples in small quantities |



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**Table 42: Analytical Methods Supplies Needed**

| Indicator Parameter | Specific Glassware | Equipment | Reagents or Kits | Unique Suppliers |
|---|---|---|---|---|
| Ammonia | Sample Cells | Spectrophotometer or Colorimeter | Hach reagents for method 8155 | www.hach.com |
| Boron | None | Spectrophotometer or Colorimeter | Hach reagents for method 10061 | www.hach.com |
| Chlorine | None | Spectrophotometer or Colorimeter | Hach reagents for method 8021 | www.hach.com |
| Color | None | None | Color Kit | www.hach.com |
| Conductivity | None | Horiba probe | Standards | www.horiba.com |
| Detergents - Surfactants (MBAS) | None | None | Chemets Detergents Test | www.chemetrics.com |
| *E. Coli* | None | Sealer<br>Black Light<br>Comparator | Colilert Reagent<br>Quanti-Tray Sheets | IDEXX Corporation<br>www.idexx.com |
| Fluorescence | Cuvettes | Fluorometer | None | Several |
| Fluoride | None | Spectrophotometer or Colorimeter | Hach reagents for method 8029 | www.hach.com |
| Hardness | Erlenmeyer Flask | Burette and Stand or<br>Digital Titrator | EDTA Cartridges or Reagent and Buffer Solution | www.hach.com |
| pH | None | Horiba Probe | Standards | www.horiba.com |
| Potassium | None | Horiba Probe | Standards | www.horiba.com |
| Potassium (Colorimetric) | None | Spectrophotometer or Colorimeter | Hach Reagents for method 8012 | www.hach.com |

## Cost

Table 43 compares the per sample cost to analyze indicator parameters. In general, the per sample cost is fairly similar for most parameters, with the exception of bacteria analyses for *E. coli*, total coliform, or Enterococci. Reagents typically cost less than $2.00 per sample, and equipment purchases seldom exceed $1,000. The typical analysis time averages less than 10 minutes per sample. More information on budgeting indicator monitoring programs can be found in Section 12.8.

**Table 43: Chemical Analysis Costs**

| Parameter | Analysis Cost | | | | |
|---|---|---|---|---|---|
| | Per Sample Costs | | | | Approximate Initial Equipment Cost (Item) |
| | Disposable supplies | Analysis Time (min/sample) | Staff Cost (@$25/hr) | Total Cost Per Sample | |
| Ammonia | $1.81 | 25[3] | $10.42 | $12.23 | $950[4] (Colorimeter) |
| Boron | $0.50 | 20[3] | $8.33 | $8.83 | $950[4] (Colorimeter) |
| Chlorine | $0.60 | 5 | $2.08 | $2.68 | $950[4] (Colorimeter) |
| Color | $0.52 | 1 | $0.42 | $0.94 | $0 |
| Conductivity | $0.65[2] | 4[3] | $1.67 | $2.32 | $275 (Probe) |
| Detergents – Surfactants[1] | $3.15 | 7 | $2.92 | $6.07 | $0 |
| Enterococci, *E. Coli* or Total Coliform[1] | $6.75 | 7 (24 hour waiting time) | $2.92 | $9.67 | $4,000 (Sealer and Incubator) |
| Fluoride[1] | $0.68 | 3 | $1.25 | $1.93 | $950[4] (Colorimeter) |
| Hardness | $1.72 | 5 | $2.08 | $3.80 | $125 (Digital Titrator) |
| pH | $0.65[2] | 3.5[3] | $1.46 | $2.11 | $250 (Probe) |
| Potassium (High Range) | $0.50[2] | 5.5[3] | $2.29 | $2.79 | $250 (Probe) |
| Potassium (Low Range) | $1.00 | 5 | $2.08 | $3.08 | $950[4] (Colorimeter) |
| Turbidity | $0.50[2] | 6[3] | $2.50 | $3.00 | $850 (Turbiditimeter) |

[1] Potentially high waste disposal cost for these parameters.
[2] The disposable supplies estimates are based on the use of standards to calibrate a probe or meter.
[3] Analysts can achieve significant economies of scale by analyzing these parameters in batches.
[4] Represents the cost of a colorimeter. The price of a spectrophotometer, which measures a wider range of parameters, is more than $2,500. This one-time cost can be shared among chlorine, fluoride, boron, potassium and ammonia.

## Additional Tips for In-house Laboratory Analysis

The following tips can help program managers with in-house laboratory analysis decisions:

- Program managers may want to use both in-house analysis and contract labs to measure the full range of indicator parameters needed in a safe and cost-effective manner. In this case, a split sample analysis strategy is used, where some samples are sent to the contract lab, while others are analyzed in house.

- Remember to order enough basic lab supplies, because they are relatively cheap and having to constantly re-order supplies and wash glassware can be time-consuming. In addition, some scientific supply companies have minimum order amounts, below which additional shipping and handling is charged.

- Be careful to craft a sample analysis schedule that doesn't interfere with other lab operations, particularly if it is a municipal lab. With appropriate preservation, many samples can be stored for several weeks.

### Considerations for Choosing a Contract Lab

When a community elects to send samples to an independent contract lab for analysis, it should investigate seven key factors:

1. Make sure that the lab is EPA-certified for the indicator parameters you choose. A state-by-state list of EPA certified labs for drinking water can be found at: http://www.epa.gov/safewater/privatewells/labs.html. State environmental agencies are also good resources to contact for pre-approved laboratories.

2. Choose a lab with a short turn-around time. Some Phase I communities had problems administering their programs because of long turn-around times from local labs (CWP, 2002). As a rule, a lab should be able to produce results within 48 hours.

3. Clearly specify the indicator parameter and analysis method you want, using the guidance in this manual or advice from a water quality expert.

4. Ensure that the maximum hold time for each indicator parameter exceeds the time it takes to ship samples to the lab for analysis.

5. Carefully review and understand the shipping and preservation instructions provided by the contract lab.

6. Look for labs that offer electronic reporting of sample results, which can greatly increase turn-around time, make data analysis easier, and improve response times.

7. Periodically check the lab's QA/QC procedures, which should include lab spikes, lab blanks, and split samples. The procedures for cleaning equipment and calibrating instruments should also be evaluated. These QA/QC procedures are described below.

    - *Lab spikes* – Samples of known concentration are prepared in the laboratory to determine the accuracy of instrument readings.

    - *Lab blanks* – Deionized water samples that have a known zero concentration are used to test methods, or in some methods to "zero" the instruments.

    - *Split samples* – Samples are divided into two separate samples at the laboratory for a comparative analysis. Any difference between the two sample results suggests the analysis method may not be repeatable.

    - *Equipment cleaning and instrument maintenance protocols* – Each lab should have specific and routine procedures to maintain equipment and clean glassware and tubing. These procedures should be clearly labeled on each piece of equipment.

- *Instrument calibration* – Depending on the method, instruments may come with a standard calibration curve, or may require calibration at each use. Lab analysts should periodically test the default calibration curve.

Table 44 summarizes estimated costs associated with sample analyses at a contract lab.

## 12.4 Techniques to Interpret Indicator Data

Program managers need to decide on the best combination of indicator parameters that will be used to confirm discharges and identify flow types. This section presents guidance on four techniques to interpret indicator parameter data:

- Flow Chart Method (recommended)
- Single Parameter Screening
- Industrial Flow Benchmarks
- Chemical Mass Balance Model (CMBM)

**Table 44: Typical Per Sample Contract Lab Costs**

| Parameter | Costs |
|---|---|
| Ammonia | $12 - $25 |
| Boron | $16 - $20 |
| Chlorine | $6 - $10 |
| Color | $7 - $11 |
| Conductivity | $2 - $6 |
| Detergents – Surfactants | $17- $35 |
| Enterococci, *E. Coli* or Total Coliform | $17 - $35 |
| Fluoride | $14 - $25 |
| Hardness | $8 - $16 |
| pH | $2 - $7 |
| Potassium | $12 - $14 |
| Turbidity | $9 - $12 |

All four techniques rely on benchmark concentrations for indicator parameters in order to distinguish among different flow types. Program managers are encouraged to adapt each technique based on local discharge concentration data, and some simple statistical methods for doing so are provided throughout the section.

### The Flow Chart Method

The Flow Chart Method is recommended for most Phase II communities, and was originally developed by Pitt *et al.* (1993) and Lalor (1994) and subsequently updated based on new research by Pitt during this project. The Flow Chart Method can distinguish four major discharge types found in residential watersheds, including sewage and wash water flows that are normally the most common illicit discharges. Much of the data supporting the method were collected in Alabama and other regions, and some local adjustment may be needed in some communities. The Flow Chart Method is recommended because it is a relatively simple technique that analyzes four or five indicator parameters that are safe, reliable and inexpensive to measure. The basic decision points involved in the Flow Chart Method are shown in Figure 47 and described below:

*Step 1: Separate clean flows from contaminated flows using detergents*

The first step evaluates whether the discharge is derived from sewage or washwater sources, based on the presence of detergents. Boron and/or surfactants are used as the primary detergent indicator, and values of boron or surfactants that exceed 0.35 mg/L and 0.25 mg/L, respectively, signal that the discharge is contaminated by sewage or washwater.

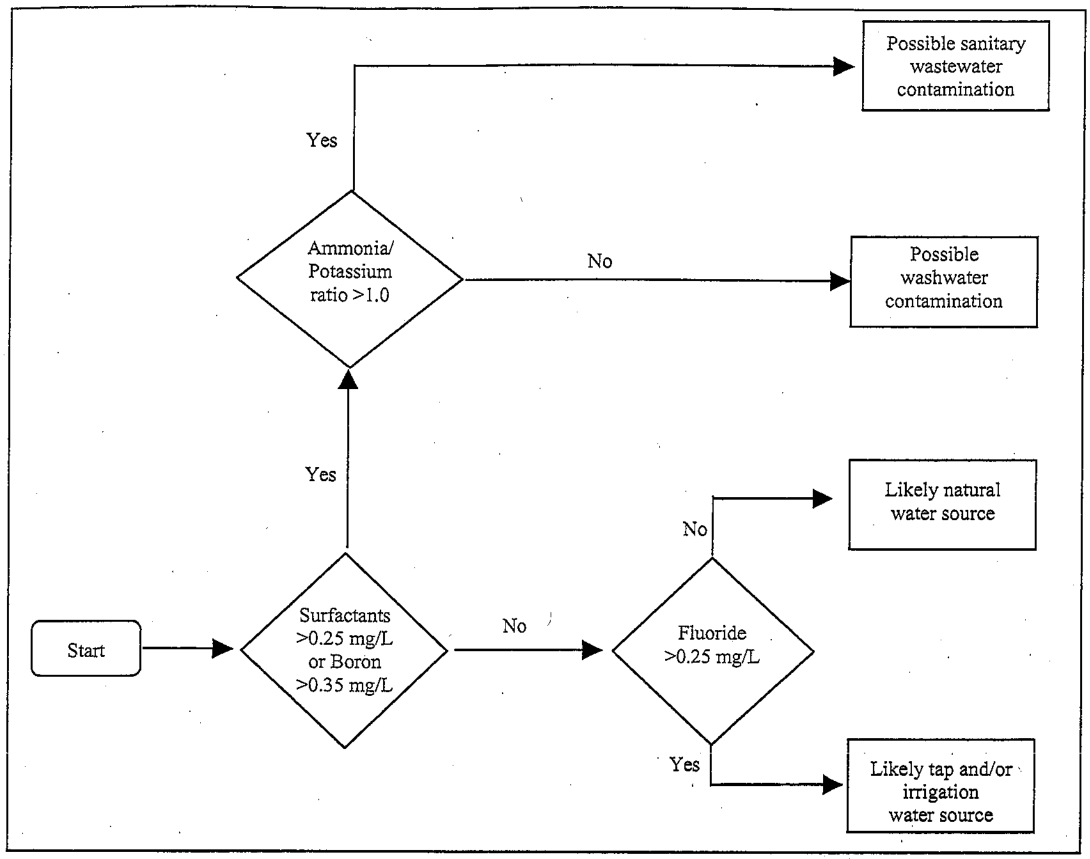


**Figure 47: Flow Chart to Identify Illicit Discharges in Residential Watersheds**

*Step 2: Separate washwater from wastewater using the Ammonia/Potassium ratio*

If the discharge contains detergents, the next step is to determine whether they are derived from sewage or washwater, using the ammonia to potassium ratios. A ratio greater than one suggests sewage contamination, whereas ratios less than one indicate washwater contamination. The benchmark ratio was developed by Pitt *et al.* (1993) and Lalor (1994) based on testing in urban Alabama watersheds.

*Step 3: Separate tap water from natural water*

If the sample is free of detergents, the next step is to determine if the flow is derived from spring/groundwater or comes from tap water. The benchmark indicator used in this step is fluoride, with concentrations exceeding 0.60 mg/L indicating that potable water is the source. Fluoride levels between 0.13 and 0.6 may indicate non-target irrigation water. The purpose of determining the source of a relatively "clean discharge" is that it can point to water line breaks, outdoor washing, non-target irrigation and other uses of municipal water that generate flows with pollutants.

## Adapting the Flow Chart Method

The Flow Chart Method is a robust tool for identifying illicit discharge types, but may need to be locally adapted, since much of the supporting data was collected in one region of the country. Program managers should look at four potential modifications to the flow chart in their community.

1) Is boron or surfactants a superior local indicator of detergents?

Surfactants are almost always a more reliable indicator of detergents, except for rare cases where groundwater has been contaminated by sewage. The disadvantage of surfactants is that the recommended analytical method uses a hazardous chemical as the reagent. Boron uses a safer analytical method. However, if boron is used as a detergent indicator, program managers should sample boron levels in groundwater and tap water, since they can vary regionally. Also, not all detergent formulations incorporate boron at high levels, so it may not always be a strong indicator.

2) Is the ammonia/potassium ratio of one the best benchmark to distinguish sewage from washwater?

The ammonia/potassium ratio is a good way to distinguish sewage from washwater, although the exact ratio appears to vary in different regions of the country. The benchmark value for the ratio was derived from extensive testing in one Alabama city. In fact, data collected in another Alabama city indicated an ammonia/potassium ratio of 0.6 distinguished sewage from wash water. Clearly, program managers should evaluate the ratio in their own community, although the proposed ratio of 1.0 should still capture the majority of sewage discharges. The ratio can be refined over time using indicator monitoring at local outfalls, or through water quality sampling of sewage and washwater flow types for the chemical library.

3) Is fluoride a good indicator of tap water?

Usually. The two exceptions are communities that do not fluoridate their drinking water or have elevated fluoride concentrations in groundwater. In both cases, alternative indicator parameters such as hardness or chlorine may be preferable.

4) Can the flow chart be expanded?

The flow chart presented in Figure 47 is actually a simplified version of a more complex flow chart developed by Pitt for this project, which is presented in Appendix H. An expanded flow chart can provide more consistent and detailed identification of flow types, but obviously requires more analytical work and data analysis. Section 12.5 provides guidance on statistical techniques to customize the flow chart method based on your local discharge data.

### *Single Parameter Screening*

Research by Lalor (1994) suggests that detergents is the best single parameter to detect the presence or absence of the most common illicit discharges (sewage and washwater). The recommended analytical method for detergents uses a hazardous reagent, so the analysis needs to be conducted in a controlled laboratory setting with proper safety equipment. This may limit the flexibility of a community if it is conducting analyses in the field or in a simple office lab.

Ammonia is another single parameter indicator that has been used by some communities with widespread or severe sewage contamination. An ammonia concentration greater than 1 mg/L is generally considered to be a positive indicator of sewage contamination. Ammonia can be analyzed in the field using a portable spectrophotometer, which allows for fairly rapid results and the ability to immediately track down sources and improper connections (see Chapter 13 for details on tracking down illicit discharges) [11]. Since ammonia can be measured in the field, crews can get fast results and immediately proceed to track down the source of the discharge using pipe testing methods (see Chapter 13 for details).

As a single parameter, ammonia has some limitations. First, ammonia by itself may not always be capable of identifying sewage discharges, particularly if they are diluted by "clean" flows. Second, while some washwaters and industrial discharges have relatively high ammonia concentrations, not all do, which increases the prospects of false negatives. Lastly, other dry weather discharges, such as non-target irrigation, can also have high ammonia concentrations that can occasionally exceed 1 mg/L. Supplementing ammonia with potassium and looking at the ammonia/potassium ratio is a simple adjustment to the single parameter approach that helps to further and more accurately characterize the discharge. Ratios greater than one indicate a sewage source, while ratios less than or equal to one indicate a washwater source. Potassium is easily analyzed using a probe (Horiba Cardy™ is the recommended probe).

[11] In-field analysis may be appropriate when tracking down illicit flows, but it is typically associated with challenging and uncontrollable conditions. Therefore, it is generally recommended that analyses be conducted in a controlled lab setting.

*Industrial Flow Benchmark*

If a subwatershed has a high density of industrial generating sites, additional indicator parameters may be needed to detect and trace these unique discharges. They are often needed because industrial and commercial generating sites produce discharges that are often not composed of either sewage or washwater. Examples include industrial process water, or wash down water conveyed from a floor drain to the storm drain system.

This guidance identifies seven indicator parameters that serve as industrial flow benchmarks to help identify illicit discharges originating from industrial and other generating sites. The seven indicators (ammonia, color, conductivity, hardness, pH, potassium and turbidity) are used to identify liquid wastes and other industrial discharges that are not always picked up by the Flow Chart Method. Table 45 summarizes typical benchmark concentrations that can distinguish between unique industrial or commercial liquid wastes. Note that two of the seven indicator parameters, ammonia and potassium, are already incorporated into the flow chart method.

Table 46 illustrates how industrial benchmark parameters can be used independently or as a supplement to the flow chart method, based on data from Alabama (Appendix E). The best industrial benchmark parameters are identified in pink shading and can distinguish industrial sources from residential washwater in 80% of samples. Supplemental indicator parameters denoted by yellow shading, can distinguish industrial source from residential washwater in 50% of samples, or roughly one in two samples.

Most industrial discharges can consistently be identified by extremely high potassium levels. However, these discharges would be misclassified as washwater when just the Flow Chart Method is used. Other benchmark parameters have value in identifying specific industrial types or operations. For example, metal plating bath waste discharges are often indicated by extremely high conductivity, hardness and potassium concentrations.

## Adapting Industrial Flow Benchmark

By their very nature, industrial and other generating sites can produce a bewildering diversity of discharges that are hard to classify. Therefore, program managers will experience some difficulty in differentiating industrial sources. Over time, the composition of industrial discharges can be refined as chemical libraries for specific industrial flow types and sources are developed. This can entail a great deal of sampling, but can reduce the number of false positive or negative readings.

**Table 45: Benchmark Concentrations to Identify Industrial Discharges**

| Indicator Parameter | Benchmark Concentration | Notes |
|---|---|---|
| Ammonia | ≥50 mg/L | • Existing "Flow Chart" Parameter<br>• Concentrations higher than the benchmark can identify a few industrial discharges. |
| Color | ≥500 Units | • Supplemental parameter that identifies a few specific industrial discharges. Should be refined with local data. |
| Conductivity | ≥2,000μS/cm | • Identifies a few industrial discharges<br>• May be useful to distinguish between industrial sources. |
| Hardness | ≤10 mg/L as $CaCO_3$<br>≥2,000 mg/L as $CaCO_3$ | • Identifies a few industrial discharges<br>• May be useful to distinguish between industrial sources. |
| pH | ≤5 | • Only captures a few industrial discharges<br>• High pH values may also indicate an industrial discharge but residential wash waters can have a high pH as well. |
| Potassium | ≥20 mg/L | • Existing "Flow Chart" Parameter<br>• Excellent indicator of a broad range of industrial discharges. |
| Turbidity | ≥1,000 NTU | • Supplemental parameter that identifies a few specific industrial discharges. Should be refined with local data. |

**Table 46: Usefulness of Various Parameters to Identify Industrial Discharges**

| Industrial Benchmark Concentration | Detergents as Surfactants (mg/L) | Ammonia (mg/L) | Potassium (mg/L) | Initial "Flow Chart" Class | Color (Units) | Conductivity (µS/cm) | Hardness (mg/L as $CaCO_3$) | pH | Turbidity (NTU) | Best Indicator Parameters to Identify This Flow Type | Additional Indicator Parameters to Identify This Flow Type |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | -- | ≥50 | ≥20 | | ≥500 | ≥2000 | ≤10 ≥2,000 | ≤5 | ≥1,000 | | |
| *Concentrations in Industrial and Commercial Flow Types* | | | | | | | | | | | |
| Automotive Manufacturer[1] | 5 | 0.6 | [redacted] | **Wash water** | 15 | 220 | 30 | 6.7 | 118 | Potassium | |
| Poultry Supplier[1] | 5 | 4.2 | [redacted] | **Wash water** | 23 | 618 | 31 | 6.3 | 111 | Potassium | |
| Roofing Product Manufacturing[1] | 8 | 10.2 | 27 | **Wash water** | >100[2] | 242 | 32 | 7.1 | 229 | None | Potassium Color |
| Uniform Manufacturing[1] | 6 | 6.1 | [redacted] | **Wash water** | >100[2] | 798 | 35 | 10.4 | 2,631 | Potassium | Color Turbidity |
| Radiator Flushing | 15 | (26.3) | [redacted] | **Wash water** | [redacted] | [redacted] | (5.6) | (7.0) | - | Potassium Conductivity Color | Hardness |
| Metal Plating Bath | 7 | [redacted] | [redacted] | **Wash water** | (104) | [redacted] | [redacted] | (4.9) | - | Ammonia Potassium Conductivity Hardness | pH |
| Commercial Car Wash | 140 | 0.9; (0.2) | 4; [redacted] | **Wash water** | >61; (222) | 274; (485) | 71; (157) | 7.7; (6.7) | 156 | | Potassium Turbidity |
| Commercial Laundry | (27) | (0.8) | 3 | **Wash water** | 47 | (563) | (36) | (9.1) | - | | |

[redacted] Supplemental indicators, shaded in yellow, distinguish this source from residential wash water in 50% of samples, or in only one community.
(Data in parentheses are mean values from Birmingham); Data not in parentheses are from Tuscaloosa
[1] Fewer than 3 samples for these discharges.
[2] The color analytical technique used had a maximum value of 100, which was exceeded in all samples. Color may be a good indicator of these industrial discharges and the benchmark concentration may need adjustment downward for this specific community.

*Chemical Mass Balance Model (CMBM) for Blended Flows*

The Chemical Mass Balance Model (CMBM) is a sophisticated technique to identify flow types at outfalls with blended flows (i.e., dry weather discharges originating from multiple sources). The CMBM, developed by Karri (2004) as part of this project is best applied in complex sewersheds with large drainage areas, and relies heavily on the local chemical library discussed in the next section.

The CMBM can quantify the fraction of each flow type present in dry weather flow at an outfall (e.g., 20% spring water; 40% sewage; 20% wash water). The CMBM relies on a computer program that generates and solves algebraic mass balance equations, based on the statistical distribution of specific flow types derived from the chemical library. The CMBM is an excellent analysis tool, but requires significant advance preparation and sampling support. More detailed guidance on how to use and interpret CMBM data can be found in Appendix I.

The chemical library requires additional statistical analysis to support the CMBM. Specifically, indicator parameter data for each flow type need to be statistically analyzed to determine the **mean**, the **coefficient of variation**, and the **distribution type**. In its current version, the CMBM accepts two distribution types: normal or lognormal distributions. Various statistical methodologies can determine the distribution type of a set of data. Much of this analysis can be conducted using standard, readily-available statistical software, such as the Engineering Statistics Handbook which is available from the National Institute of Standards and Technology, and can be accessed at http://www.itl.nist.gov/div898/handbook/.

## 12.5 The Chemical Library

The chemical library is a summary of the chemical composition of the range of discharge types found in a community. The primary purpose of the library is to characterize distinct flow types that may be observed at outfalls, including both clean and contaminated discharges. A good library includes data on the composition of tap water, groundwater, sewage, septage, non-target irrigation water, industrial process waters, and washwaters (e.g., laundry, car wash, etc.). The chemical library helps program managers customize the flow chart method and industrial benchmarks, and creates the input data needed to drive the CMBM.

To develop the library, samples are collected directly from the discharge source (e.g., tap water, wastewater treatment influent, shallow wells, septic tanks, etc.). Table 47 provides guidance on how and where to sample each flow type in your community. As a general rule, about 10 samples are typically needed to characterize each flow type, although more samples may be needed if the flow type has a high coefficient of variation. The measure of error can be statistically defined by evaluating the coefficient of variation of the sample data (variability relative to the mean value), and the statistical distribution for the data (the probable spread in the data beyond the mean). For more guidance on statistical techniques for assessing sampling data, consult Burton and Pitt (2002) and US EPA (2002), which can be accessed at http://galton.uchicago.edu/~cises/resources/EPA-QA-Sampling-2003.pdf.

Chemical libraries should also be compared to databases that summarize indicator monitoring of dry weather flows at suspect outfalls. Outfall samples may not always be representative of individual flow types because of mixing of flows and dilution, but they can serve as a valuable check if the discharge source is actually confirmed. Program managers can also use both the chemical library and indicator database to refine flow chart or industrial benchmarks (see Appendix J for an example).

Over time, communities may want to add other flow types to the chemical library, such as transitory discharges that generate small volume flows such as "dumpster juice," power washing and residential car washing. Transitory discharges are hard to detect with outfall monitoring, but may cumulatively contribute significant dry weather loads. Understanding the chemical makeup of the transitory discharges can help program managers prioritize education and pollution prevention efforts.

**Table 47: Where and How to Sample for Chemical "Fingerprint" Library**

| Flow Type | Places to Collect the Data | Any Other Potential Sources? |
|---|---|---|
| Shallow Groundwater | • From road cuts or stream banks<br>• Samples from shallow wells<br>• USGS regional groundwater quality data<br>• Dry weather in-stream flows at headwaters with no illicit discharges | None. Locally distinct. |
| Spring Water | • Directly from springs | None. Locally distinct. |
| Tap water | • Individual taps throughout the community<br>• or analyze local drinking water monitoring reports or annual consumer confidence reports | None. Locally distinct |
| Irrigation | • Collect irrigation water from several different sites. May require a hand operated vacuum pump to collect these shallow flows (see Burton and Pitt, 2002) | None. Locally distinct. |
| Sewage | • Reported sewage treatment plant influent data provides a characterization of raw sewage and is usually available from discharge monitoring reports. Because the characteristics of sewage will vary within the collection system depending upon whether the area is serving residential or commercial uses, climate, residence time in the collection system, etc, it is often more accurate and valuable to collect "fingerprint" samples from within the system, rather than at the treatment plant. | Data in Appendix E can provide a starting point, but local data are preferred. |
| Septage | • Outflow of several individual septic tanks or leach fields | |
| Most Industrial Discharges | • Direct effluent from the industrial process (Obtain samples as part of industrial pre-treatment program in local community) | Data in Appendix E characterize some specific industrial flows. Industrial NPDES permit monitoring can also be used. |
| Commercial Car Wash; Commercial Laundry | • Sumps at these establishments | Data in Appendix E can provide a starting point, but local data are preferred. |

### *Evaluating Interpretive Techniques Using Outfall Indicator Monitoring Data*

Outfall sampling data for confirmed sources or flow types can be used to test the accuracy and reliability of all four interpretive techniques. The sampling record is used to determine the number of false positives or false negatives associated with a specific interpretive technique. A simple tabulation of false test readings can identify the types and levels of indicator parameters that are most useful.

Table 48 provides an example of how the Flow Chart Method was tested with outfall monitoring data from Birmingham, AL (Pitt *et al.*, 1993). In this case, the Flow Chart Method was applied without adaptation to local conditions, and the number of correctly (and incorrectly) identified discharges was tracked. Tests on 10 Birmingham outfalls were mostly favorable, with the flow chart method correctly identifying contaminated discharges in all cases (i.e., washwater or sewage waste water). At one outfall, the flow chart incorrectly identified sewage as washwater, based on an ammonia ($NH_3$)/ potassium (K) ratio of 0.9 that was very close to the breakpoint in the Flow Chart Method (ratio of one). Based on such tests, program managers may want to slightly adjust the breakpoints in the Flow Chart Method to minimize the occurrence of errors.

## 12.6 Special Monitoring Techniques for Intermittent or Transitory Discharges

The hardest discharges to detect and test are intermittent or transitory discharges to the storm drain system that often have an indirect mode of entry. With some ingenuity, luck, and specialized sampling techniques, however, it may be possible to catch these discharges. This section describes some specific monitoring techniques to track down intermittent discharges. Transitory discharges cannot be reliably detected using conventional outfall monitoring techniques, and are normally found as a result of hotline complaints or spill events. Nevertheless, when transitory discharges are encountered, they should be sampled if possible.

### *Techniques for Monitoring Intermittent Discharges*

An outfall may be suspected of having intermittent discharges based on physical indicators (e.g., staining), poor in-stream dry weather water quality, or the density of generating sites in the contributing subwatershed. The only sure way to detect an intermittent discharge is to camp out at the outfall for a long period of time, which is obviously not very cost-effective or feasible. As an alternative, five special monitoring techniques can be used to help track these elusive problems:

- Odd hours monitoring
- Optical brightener monitoring traps
- Caulk dams
- Pool sampling
- Toxicity monitoring

**Table 48: Evaluation of the Flow Chart Method Using Data from Birmingham, Alabama**
*(Adapted from Pitt et al., 1993)*

| Outfall ID | Outfall Concentrations (mg/L) Detergents-Surfactants (>0.25 is sanitary or wash water) | $NH_3$ | K | $NH_3$/K (>1.0 is sanitary) | Fluoride (>0.25 is tap, if no detergents) | Predicted Flow Type | Confirmed Flow Type | Result |
|---|---|---|---|---|---|---|---|---|
| 14 | 0 | 0 | 0.69 | 0.0 | 0.04 | Natural Water | Spring Water | Correct |
| 20 | 0 | 0.03 | 1.98 | 0.0 | 0.61 | Tap Water | Rinse Water (Tap) and Spring Water | Correct |
| 21 | 20 | 0.11 | 5.08 | 0.0 | 2.80 | Washwater | Washwater (Automotive) | Correct |
| 26 | 0 | 0.01 | 0.72 | 0.0 | 0.07 | Natural Water | Spring Water | Correct |
| 28 | 0.25[1] | 2.89 | 5.96 | 0.5 | 0.74 | Washwater | Washwater (Restaurant) | Correct |
| 31 | 0.95 | 0.21 | 3.01 | 0.1 | 1.00 | Washwater | Laundry (Motel) | Correct |
| 40z | 0.25[1] | 0.87 | 0.94 | 0.9 | 0.12 | Washwater | Shallow Groundwater and Septage | Identifies Contaminated but Incorrect Flow Type |
| 42 | 0 | 0 | 0.81 | 0.0 | 0.07 | Natural Water | Spring Water | Correct |
| 48 | 3.0 | 5.62 | 4.40 | 1.3 | 0.53 | Sanitary Wastewater | Spring Water and Sewage | Correct |
| 60a | 0 | 0.31 | 2.99 | 0.1 | 0.61 | Tap Water | Landscaping Irrigation Water | Correct |

[1] These values were increased from reported values of 0.23 mg/L (outfall 28) and 0.2 mg/L (outfall 40z). The analytical technique used in Birmingham was more precise (but more hazardous) than the method used to develop the flow chart in Figure 47. It is assumed that these values would have been interpreted as 0.25 mg/L using the less precise method.

## Odd Hours Monitoring

Many intermittent discharges actually occur on a regular schedule, but unfortunately not the same one used by field crews during the week. For example, some generating sites discharge over the weekend or during the evening hours. If an outfall is deemed suspicious, program managers may want to consider scheduling "odd hours" sampling at different times of the day or week. Some key times to visit suspicious outfalls include:

- Both morning and afternoon
- Weekday evenings
- Weekend mornings and evenings

## Optical Brightener Monitoring Traps

Optical brightener monitoring (OBM) traps are another tool that crews can use to gain insight into the "history" of an outfall without being physically present. OBM traps can be fabricated and installed using a variety of techniques and materials. All configurations involve an absorbent, unbleached cotton pad or fabric swatch and a holding or anchoring device such as a wire mesh trap (Figure 48) or a section of small diameter (e.g., 2-inch) PVC pipe. Traps are anchored to the inside of outfalls at the invert using wire or monofilament that is secured to the pipe itself or rocks used as temporary weights.

Field crews retrieve the OBM traps after they have been deployed for several days of dry weather, and place them under a fluorescent light that will indicate if they have been exposed to detergents. OBM traps have been used with some success in Massachusetts (Sargent *et al.*, 1998) and northern Virginia (Waye, 2000). Although each community used slightly different methods, the basic sampling concept is the same. For more detailed guidance on how to use OBM traps and interpret the results, consult the guidance manual found at: http://www.naturecompass.org/8tb/sampling/index.html and http://www.novaregion.org/obm.htm.

Although OBM traps appear useful in detecting some intermittent discharges, research during this project has found that OBM traps only pick up the most contaminated discharges, and the detergent level needed to produce a "hit" was roughly similar to pure washwater from a washing machine (see Appendix F for results). Consequently, OBM traps may be best suited as a simple indicator of presence or absence of intermittent flow or to detect the most concentrated flows. OBM traps need to be retrieved before runoff occurs from the outfalls, which will contaminate the trap or wash it away.

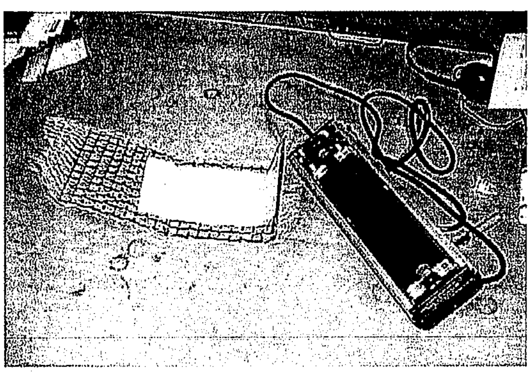

**Figure 48: OBM Equipment includes a black light and an OBM Trap that can be placed at an outfall**
*Source: R. Pitt*

## Caulk Dams

This technique uses caulk, plumber's putty, or similar substance to make a dam about two inches high within the bottom of the storm drain pipe to capture any dry weather flow that occurs between field observations. Any water that has pooled behind the dam is then sampled using a hand-pump sampler, and analyzed in the lab for appropriate indicator parameters.

## Pool Sampling

In this technique, field crews collect indicator samples directly from the "plunge pool" below an outfall, if one is present. An upstream sample is also collected to characterize background stream or ditch water quality that is not influenced by the outfall. The pool water and stream sample are then analyzed for indicator parameters, and compared against each other. Pool sampling results can be constrained by stream dilution, deposition, storm water flows, and chemical reactions that occur within the pool.

## Toxicity Monitoring

Another way to detect intermittent discharges is to monitor for toxicity in the pool below the outfall on a daily basis. Burton and Pitt (2002) outline several options to measure toxicity, some of which can be fairly expensive and complex. The Fort Worth Department of Environmental Management has developed a simple low-cost outfall toxicity testing technique known as the Stream Sentinel program. Stream sentinels place a bottle filled with minnows in the pool below suspected outfalls and measure the survival rate of the minnows as an indicator of the toxicity of the outfall [12] (see Figure 49).

One advantage of the sentinel program is that volunteer monitors can easily participate, by raising and caring for the minnows, placing bottles at outfalls, and visiting them everyday to record mortality. The long-term nature of sentinel monitoring can help pick up toxicity trends at a given outfall. For example, Fort Worth observed a trend of mass mortality on the second Tuesday of each month at some outfalls, which helped to pinpoint the industry responsible for the discharges, and improved sample scheduling (City of Fort Worth, 2003). More information about the Stream Sentinel program can be found at: www.fortworthgov.org/DEM/stream_sentinel.pdf.

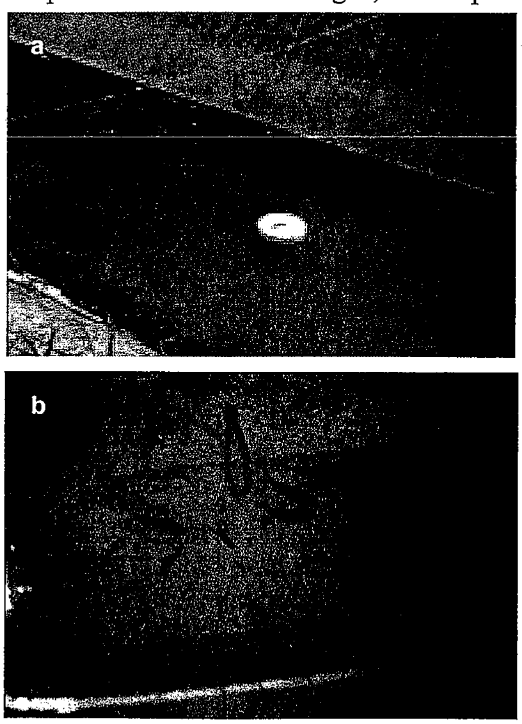


**Figure 49: Float and wire system to suspend a bottle in a stream sentinel station deployed in Fort Worth, TX (a); Minnows in the perforated bottle below the water surface (b).**

Due to the cost and difficulty of interpreting findings, toxicity testing is generally not recommended for communities unless they have prior experience and expertise with the method.

### *Techniques for Monitoring Transitory Discharges*

Transitory discharges, such as spills and illegal dumping, are primarily sampled to assign legal responsibility for enforcement actions or to reinforce ongoing pollution prevention education efforts. In most cases, crews attempt to trace transitory discharges back up the pipe or drainage area using visual techniques (see Chapter 13). However, field crews should always collect a sample to document the event. Table 49 summarizes some follow-up monitoring strategies to document transitory discharges.

## 12.7 Monitoring of Stream Quality During Dry Weather

In-stream water quality monitoring can help detect sewage and other discharges in a community or larger watershed. Stream monitoring can identify the subwatersheds with the greatest illicit or sewage discharge potential that is then used to target outfall indicator monitoring. At the smaller reach scale, stream monitoring may sometimes detect major individual discharges to the stream.

[12] It may be necessary to obtain approval from the appropriate state of federal regulatory agency before conducting toxicity monitoring using vertebrates.

| Table 49: Follow-Up Monitoring for Transitory Discharges | |
|---|---|
| Condition | Response |
| Oils or solvents | Special hydrocarbon analysis to characterize the source of the oil |
| Unknown but toxic material | Full suite of metals, pesticides, other toxic materials |
| Probable sewage | Monitor for parameters associated with the Flow Chart Technique (detergents, ammonia, potassium, fluoride) for residential drainage areas |

### *Stream Monitoring to Identify Problem Reaches or Subwatersheds*

Stream monitoring data can be used to locate areas in subwatersheds where illicit discharges may be present, and where human or aquatic health risks are higher. To provide this information, stream monitoring should be conducted regularly during dry weather conditions to track water quality (at least monthly) and to document changes in water quality over a period of time. Stream monitoring data are particularly effective when combined with ORI data. For example, a subwatershed with many ORI physical indicators of illicit discharges (e.g., a high number of flowing outfalls) that also has poor stream water quality would be an obvious target for intensive outfall monitoring.

Stream monitoring parameters should reflect local water quality goals and objectives, and frequently include bacteria and ammonia. Bacteria are useful since sewage discharges can contribute to violations of water contact standards set for recreation during dry weather conditions. Table 50 summarizes water quality standards for *E. coli* that EPA recommends for water contact recreation. It is important to note that individual states may use different action levels or bacteria indicators (e.g., Enterococci or fecal coliform) to regulate water contact recreation. For a review of the impacts bacteria exert on surface waters, consult CWP (2000).

An important caveat when interpreting stream monitoring data is that a violation of bacteria standards during dry weather flow does not always mean that an illicit discharge or sewage overflow is present. While raw sewage has bacteria concentrations that greatly exceed bacteria standards (approximately 12,000 MPN/100 mL) other bacteria sources, such as urban wildlife, can also cause a stream to violate standards. Consequently, stream monitoring data need to be interpreted in the context of other information, such as upstream land use, past complaints, age of infrastructure, and ORI surveys.

Ideally, stream monitoring stations should be strategically located with a minimum of one station per subwatershed, and additional stations at stream confluences and downstream of reaches with a high outfall density. Stations should also be located at beaches, shellfish harvesting and other areas where discharges represent a specific threat to public health. See Burton and Pitt (2002) for guidance on stream monitoring.

### *Stream Monitoring to Identify Specific Discharges*

Stream monitoring data can help field crews locate individual discharges within a specific stream reach. Immediate results are needed for this kind of monitoring, so indicator parameters should be analyzed using simple field test kits or portable analytical instruments (e.g., spectrophotometer). Bacteria is not a good indicator parameter to use for this purpose because lab results cannot be received for at least one day (analytical method requires a "hold time" of 24 hours). Table 51 summarizes nutrient indicator parameters along with their "potential problem level" benchmarks. It is important to note that other factors, such as animal operations, can elevate stream nutrient concentrations, so data should always be interpreted in the context of surrounding land use. Stream monitoring benchmarks should be continuously refined as communities develop a better understanding of what dry weather baseline concentrations to expect.

If stream monitoring indicates that a potential problem level benchmark has been exceeded, field crews continue stream sampling to locate the discharge through a process of elimination. Crews walk upstream taking regular samples above and below stream confluences until the benchmark concentration declines. The crews then take samples at strategic points to narrow down the location of the discharge, using the in-pipe monitoring strategy described in Chapter 13.

**Table 50: Typical "Full Body Contact Recreation" Standards for *E. coli***
*(Source: EPA, 1986)*[1]

| Use | Criterion |
|---|---|
| Designated beach area | 235 MPN /100 mL |
| Moderately-used full body contact recreation area | 298 MPN /100 mL |
| Lightly-used full body contact recreation | 406 MPN /100 mL |
| Infrequently-used full body contact recreation | 576 MPN /100 mL |

[1] *These concentrations represent standards for a single sampling event. In all waters, a geometric mean concentration of 126 MPN/100 mL cannot be exceeded for five samples taken within one month.*

**Table 51: Example In-Stream Nutrient Indicators of Discharges**
*(Zielinski, 2003)*

| Parameter | Potential Problem Level* | Possible Cause of Water Quality Problem |
|---|---|---|
| Total Nitrogen (TN) | 3.5 mg/l | High nutrients in ground water from agriculture, lawn practices, or sewage contamination from illicit connection, sanitary line break or failing septic system. |
| Total Phosphorus (TP) | 0.4 mg/l | Contamination from lawn practices, agriculture, sewage or washwater. |
| Ammonia ($NH_3$) | 0.3 mg/l | Sewage or washwater contamination from illicit connection, sanitary line break or failing septic system. |

**Nutrient parameters are based on USGS NAWQA data with 85% of flow weighted samples being less than these values in urban watersheds (Note: data from Nevada were not used, due to climatic differences and for some parameters they were an order of magnitude higher). Communities can modify these benchmarks to reflect local data and experience.*

## 12.8 The Costs of Indicator Monitoring

This section provides general guidance on scoping and budgeting an indicator monitoring program. The required budget will ultimately be dictated by the monitoring decisions and local conditions within a community. The budgeting data presented in this section are based on the level of indicator sampling effort in two hypothetical communities, using different numbers of samples, indicator parameters, and analysis methods.

### Budgets for Indicator Monitoring in a Hypothetical Community

Communities can develop annual budgets for indicator monitoring if the degree of sampling effort can be scoped. This is normally computed based on the expected number of samples to analyze and is a function of stream miles surveyed and outfall density. For example, if a community collects samples from 10 stream miles with eight outfalls per mile, it will have 80 samples to analyze. This number can be used to generate start-up and annual monitoring cost estimates that represent the expected level of sampling effort. Table 52 summarizes how indicator monitoring budgets were developed for two hypothetical communities, each with 80 outfalls to sample. Budgets are shown using both in-house and contract lab set-ups, and are split between initial start-up costs and annual costs.

*Community A: Primarily Residential Land Use, Flow Chart Method*

In this scenario, six indicator parameters were analyzed, several of which were used to support the Flow Chart Method. The community took no additional samples to create a chemical library, and instead relied on default values to identify illicit discharges. The community analyzed the samples in-house at a rate of one sample (includes analysis of all six parameters) per staff hour.

*Community B: Mixed Land Use - Multiple Potential Sources, Complex Analysis*

In the second scenario, the community analyzed 11 indicator parameters, including a bacteria indicator, and took samples of eight distinct flow types to create a chemical library, for a total of 88 samples. The community analyzed the samples in-house at a rate of one sample per 1.5 staff hours.

Some general rules of thumb that were used for this budget planning example include the following:

- $500 in initial sampling equipment (e.g., sample bottles, latex gloves, dipper, cooler, etc).
- Outfall samples are collected in batches of 10. Each batch of samples can be collected and transported to the lab in two staff days (two-person crew required to collect samples for safety purposes).
- Staff rate is $25/hr.
- Overall effort to collect samples for the chemical library and statistically analyze the data is approximately one staff day per source type.
- The staff time needed to prepare for field work and interpret lab results is roughly two times that required for conducting the field work (i.e., eight days of collecting samples requires 16 days of pre- and post-preparation).

*Costs for Intermittent Discharge Analyses*

Equipment costs for most specialized intermittent discharge techniques tend to be low (<$500), and are dwarfed by staff effort.

As a rule of thumb, assume about four hours of staff time to deploy, retrieve and analyze samples collected from a single outfall using these techniques.

**Table 52: Indicator Monitoring Costs: Two Scenarios**

| | Community A: In-House | Community A: Contract Lab | Community B: In-House | Community B: Contract Lab |
|---|---|---|---|---|
| ***Initial Costs*** | | | | |
| Initial Sampling Supplies and Lab Equipment [1] | $1,700 | $500 | $7,500 | $500 |
| Staff Cost: Library Development [2] | $0 | $0 | $4,600[3] | $2,000 |
| Analysis Costs: Library Development (Reagents or Contract Lab Cost) | $0 | $0 | $1,400 | $13,000[4] |
| Total Initial Costs | **$1,700** | **$500** | **$13,500** | **$15,500** |
| ***Annual Costs in Subsequent Years*** | | | | |
| Staff Field Cost (Sample Collection) [2, 5, 6] | $3,200 | $3,200 | $3,200 | $3,200 |
| Staff Costs: Chemical Analysis [2] | $2,000 | $200[7] | $3,000 | $200 |
| Staff Time to Enter/ Interpret Data [2, 6] | $3,200 | $3,200 | $4,800 | $4,800 |
| Analysis Costs: Annual Outfall Sampling (Reagents or Contract Lab Cost) | $600 | $8,400[4] | $1,400 | $13,000[4] |
| ***TOTAL ANNUAL COST*** | **$9,000** | **$15,000** | **$12,400** | **$21,200** |

*Notes:*
[1] $500 in initial sampling equipment.
[2] Samples can be shipped to a contract lab using one staff hour.
[3] Overall effort to collect samples for the library and statistically analyze the data is approximately one staff day per source type.
[4] For contract lab analysis, assume a cost that is an average between the two extremes of the range in Table 43.
[5] Outfall samples are collected in batches of 10. Each batch of samples can be collected and transported to the lab in two staff days (two-person crew required to collect samples for safety purposes).
[6] Assume that the staff time needed to interpret lab results and prepare for field work is roughly 16 staff days. An additional eight days are required for the flow type pre- and post-preparation for Community 2.
[7] Staff rate is $25/hr.

# Chapter 13: Tracking Discharges To A Source

Once an illicit discharge is found, a combination of methods is used to isolate its specific source. This chapter describes the four investigation options that are introduced below.

*Storm Drain Network Investigation*

Field crews strategically inspect manholes within the storm drain network system to measure chemical or physical indicators that can isolate discharges to a specific segment of the network. Once the pipe segment has been identified, on-site investigations are used to find the specific discharge or improper connection.

*Drainage Area Investigation*

This method relies on an analysis of land use or other characteristics of the drainage area that is producing the illicit discharge. The investigation can be as simple as a "windshield" survey of the drainage area or a more complex mapping analysis of the storm drain network and potential generating sites. Drainage area investigations work best when prior indicator monitoring reveals strong clues as to the likely generating site producing the discharge.

*On-site Investigation*

On-site methods are used to trace the source of an illicit discharge in a pipe segment, and may involve dye, video or smoke testing within isolated segments of the storm drain network.

*Septic System Investigation*

Low-density residential watersheds may require special investigation methods if they are not served by sanitary sewers and/or storm water is conveyed in ditches or swales. The major illicit discharges found in low-density development are failing septic systems and illegal dumping. Homeowner surveys, surface inspections and infrared photography have all been effectively used to find failing septic systems in low-density watersheds.

## 13.1 Storm Drain Network Investigations

This method involves progressive sampling at manholes in the storm drain network to narrow the discharge to an isolated pipe segment between two manholes. Field crews need to make two key decisions when conducting a storm drain network investigation—where to start sampling in the network and what indicators will be used to determine whether a manhole is considered clean or dirty.

*Where to Sample in the Storm Drain Network*

The field crew should decide how to attack the pipe network that contributes to a problem outfall. Three options can be used:

- Crews can work progressively up the trunk from the outfall and test manholes along the way.
- Crews can split the trunk into equal segments and test manholes at strategic junctions in the storm drain system.
- Crews can work progressively down from the upper parts of the storm drain network toward the problem outfall.

The decision to move up, split, or move down the trunk depends on the nature and land use of the contributing drainage area. Some guidance for making this decision is provided in Table 53. Each option requires different levels of advance preparation. Moving up the trunk can begin immediately when an illicit discharge is detected at the outfall, and only requires a map of the storm drain system. Splitting the trunk and moving down the system require a little more preparation to analyze the storm drain map to find the critical branches to strategically sample manholes. Accurate storm drain maps are needed for all three options. If good mapping is not available, dye tracing can help identify manholes, pipes and junctions, and establish a new map of the storm drain network.

### Option 1: Move up the Trunk

Moving up the trunk of the storm drain network is effective for illicit discharge problems in relatively small drainage areas. Field crews start with the manhole closest to the outfall, and progressively move up the network, inspecting manholes until indicators reveal that the discharge is no longer present (Figure 50). The goal is to isolate the discharge between two storm drain manholes.

**Table 53: Methods to Attack the Storm Drain Network**

| Method | Nature of Investigation | Drainage System | Advance Prep Required |
|---|---|---|---|
| Follow the discharge up | Narrow source of an individual discharge | Small diameter outfall (< 36")<br>Simple drainage network | No |
| Split into segments | Narrow source of a discharge identified at outfall | Large diameter outfall (> 36"),<br>Complex drainage<br>Logistical or traffic issues may make sampling difficult. | Yes |
| Move down the storm drain | Multiple types of pollution, many suspected problems – possibly due to old plumbing practices or number of NPDES permits | Very large drainage area (> one square mile). | Yes |

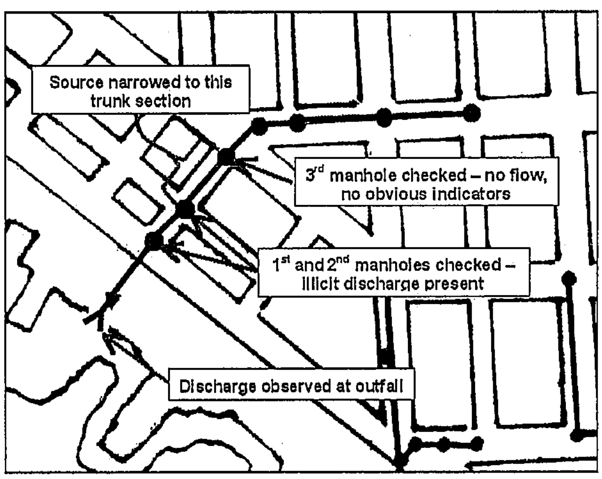


**Figure 50: Example Investigation Following the Source up the Storm Drain System**



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Option 2: Split the storm drain network

When splitting the storm drain network, field crews select strategic manholes at junctions in the storm drain network to isolate discharges. This option is particularly suited in larger and more complex drainage areas since it can limit the total number of manholes to inspect, and it can avoid locations where access and traffic are problematic.

The method for splitting the trunk is as follows:

1. Review a map of the storm drain network leading to the suspect outfall.
2. Identify major contributing branches to the trunk. The trunk is defined as the largest diameter pipe in the storm drain network that leads directly to the outfall. The "branches" are networks of smaller pipes that contribute to the trunk.
3. Identify manholes to inspect at the farthest downstream node of each contributing branch and one immediately upstream (Figure 51).
4. Working up the network, investigate manholes on each contributing branch and trunk, until the source is narrowed to a specific section of the trunk or contributing branch.
5. Once the discharge is narrowed to a specific section of trunk, select the appropriate on-site investigation method to trace the exact source.
6. If narrowed to a contributing branch, move up or split the branch until a specific pipe segment is isolated, and commence the appropriate on-site investigation to determine the source.

Option 3: Move down the storm drain network

In this option, crews start by inspecting manholes at the "headwaters" of the storm drain network, and progressively move down pipe. This approach works best in very large drainage areas that have many potential continuous and/or intermittent discharges. The Boston Water and Sewer Commission has employed the headwater option to investigate intermittent discharges in complex drainage areas up to three square miles (Jewell, 2001). Field crews certify that each upstream branch of the storm drain network has no contributing discharges before moving down pipe to a "junction manhole" (Figure 52). If discharges are found, the crew performs dye testing to pinpoint the discharge. The crew then confirms that the discharge is removed before moving farther down the pipe network. Figure 53 presents a detailed flow chart that describes this option for analyzing the storm drain network.

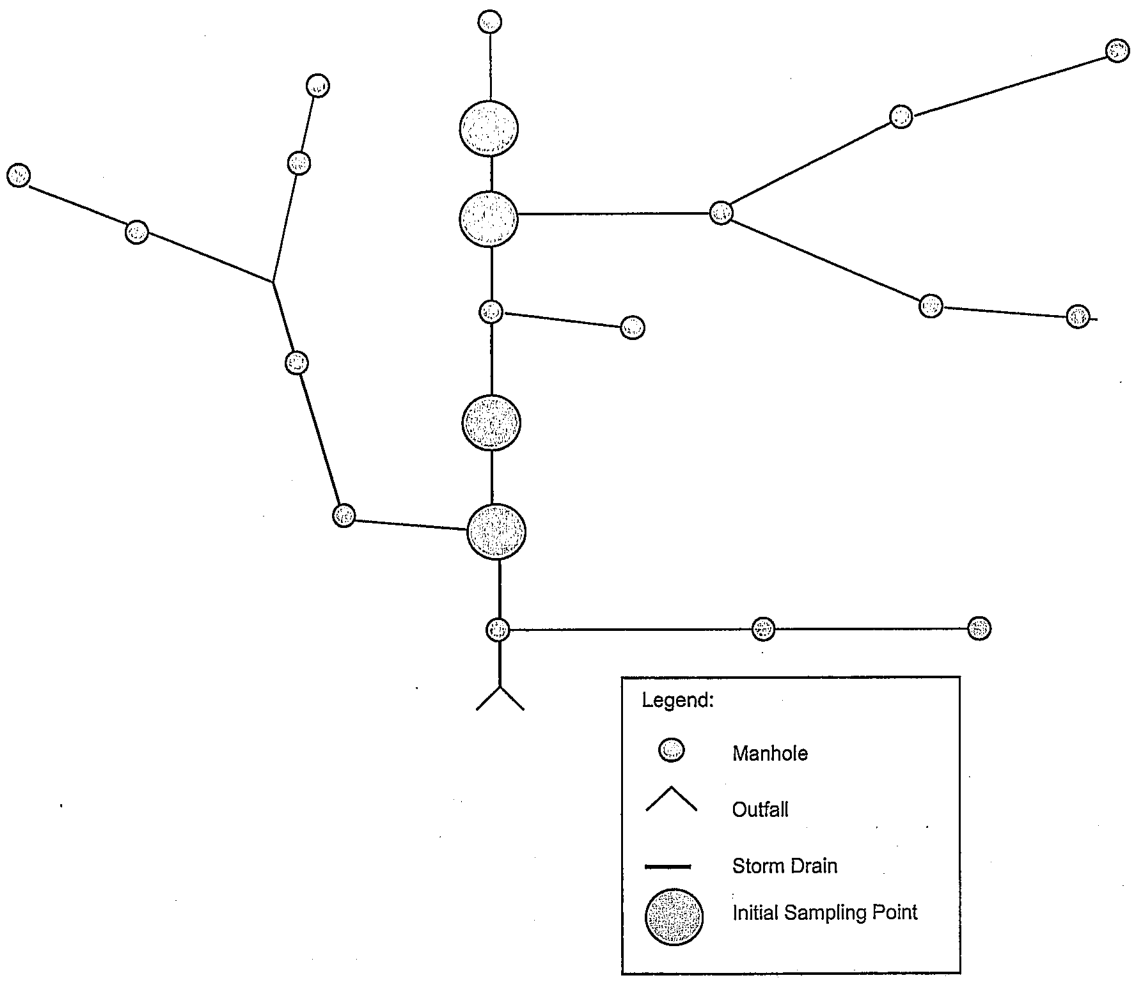


**Figure 51: Key initial sampling points along the trunk of the storm drain**



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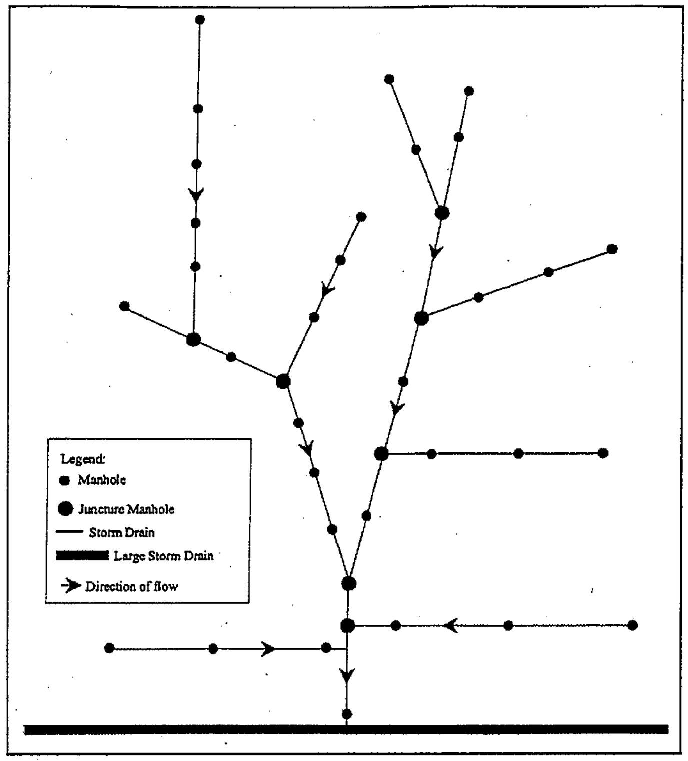


Figure 52: Storm Drain Schematic Identifying "Juncture Manholes" (Source: Jewell, 2001)

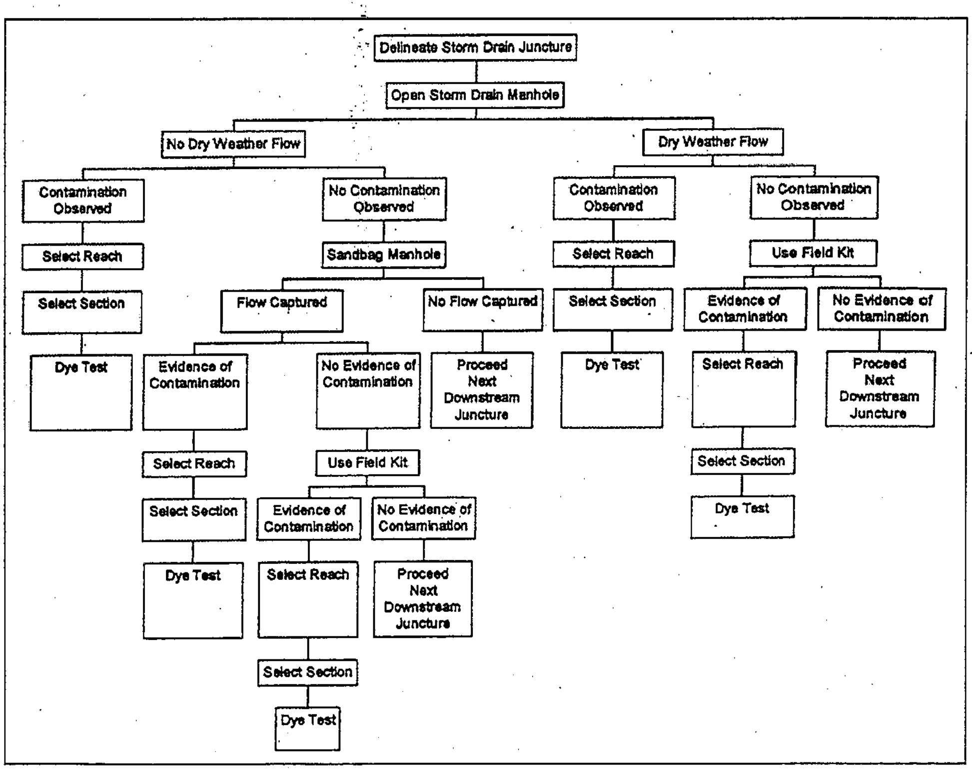


Figure 53: A Process for Following Discharges Down the Pipe
(Source: Jewell, 2001)

## Dye Testing to Create a Storm Drain Map

As noted earlier, storm drain network investigations are extremely difficult to perform if accurate storm drain maps are not available. In these situations, field crews may need to resort to dye testing to determine the flowpath within the storm drain network. Fluorescent dye is introduced into the storm drain network and suspected manholes are then inspected to trace the path of flow through the network (U.S. EPA, 1990). Two or three member crews are needed for dye testing. One person drops the dye into the trunk while the other(s) looks for evidence of the dye down pipe.

To conduct the investigation, a point of interest or down pipe "stopping point" is identified. Dye is then introduced into manholes upstream of the stopping point to determine if they are connected. The process continues in a systematic manner until an upstream manhole can no longer be determined, whereby a branch or trunk of the system can be defined, updated or corrected. More information on dye testing methods is provided in Section 13.3.

## Manhole Inspection: Visual Observations and Indicator Sampling

Two primary methods are used to characterize discharges observed during manhole inspections—visual observations and indicator sampling. In both methods, field crews must first open the manhole to determine whether an illicit discharge is present. Manhole inspections require a crew of two and should be conducted during dry weather conditions.

Basic field equipment and safety procedures required for manhole inspections are outlined in Table 54. In particular, field crews need to be careful about how they will safely divert traffic (Figure 54). Other safety considerations include proper lifting of manhole covers to reduce the potential for back injuries, and testing whether any toxic or flammable fumes exist within the manhole before the cover is removed. Wayne County, MI has developed some useful operational procedures for inspecting manholes, which are summarized in Table 55.

**Table 54: Basic Field Equipment Checklist**

| | |
|---|---|
| • Camera and film or digital camera | • Storm drain, stream, and street maps |
| • Clipboards | • Reflective safety vests |
| • Field sheets | • Rubber / latex gloves |
| • Field vehicle | • Sledgehammer |
| • First aid kit | • Spray paint |
| • Flashlight or spotlight | • Tape measures |
| • Gas monitor and probe | • Traffic cones |
| • Manhole hook / crow bar | • Two-way radios |
| • Mirror | • Waterproof marker/pen |
| • Hand held global positioning satellite (GPS) system receiver (best resolution available within budget, at least 6' accuracy) | |

**Figure 54: Traffic cones divert traffic from manhole inspection area**



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| Table 55: Field Procedure for Removal of Manhole Covers<br>*(Adapted from: Pomeroy et al., 1996)* |
|---|
| **Field Procedures:**<br>1. Locate the manhole cover to be removed.<br>2. Divert road and foot traffic away from the manhole using traffic cones.<br>3. Use the tip of a crowbar to lift the manhole cover up high enough to insert the gas monitor probe. Take care to avoid creating a spark that could ignite explosive gases that may have accumulated under the lid. Follow procedures outlined for the gas monitor to test for accumulated gases.<br>4. If the gas monitor alarm sounds, close the manhole immediately. Do not attempt to open the manhole until some time is allowed for gases to dissipate.<br>5. If the gas monitor indicates the area is clear of hazards, remove the monitor probe and position the manhole hook under the flange. Remove the crowbar. Pull the lid off with the hook.<br>6. When testing is completed and the manhole is no longer needed, use the manhole hook to pull the cover back in place. Make sure the lid is settled in the flange securely.<br>7. Check the area to ensure that all equipment is removed from the area prior to leaving. |
| **Safety Considerations:**<br>1. Do not lift the manhole cover with your back muscles.<br>2. Wear steel-toed boots or safety shoes to protect feet from possible crushing injuries that could occur while handling manhole covers.<br>3. Do not move manhole covers with hands or fingers.<br>4. Wear safety vests or reflective clothing so that the field crew will be visible to traffic.<br>5. Manholes may only be entered by properly trained and equipped personnel and when all OSHA and local rules are followed. |

## Visual Observations During Manhole Inspection

Visual observations are used to observe conditions in the manhole and look for any signs of sewage or dry weather flow. Visual observations work best for obvious illicit discharges that are not masked by groundwater or other "clean" discharges, as shown in Figure 55. Typically, crews progressively inspect manholes in the storm drain network to look for contaminated flows. Key visual observations that are made during manhole inspections include:

- Presence of flow
- Colors
- Odors
- Floatable materials
- Deposits or stains (intermittent flows)

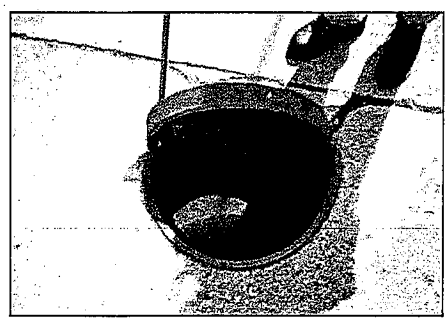

**Figure 55: Manhole observation (left) indicates a sewage discharge. Source is identified at an adjacent sewer manhole that overflowed into the storm drain system (right).**

Indicator Sampling

If dry weather flow is observed in the manhole, the field crew can collect a sample by attaching a bucket or bottle to a tape measure/rope and lowering it into the manhole (Figure 56). The sample is then immediately analyzed in the field using probes or other tests to get fast results as to whether the flow is clean or dirty. The most common indicator parameter is ammonia, although other potential indicators are described in Chapter 12.

Manhole indicator data is analyzed by looking for "hits," which are individual samples that exceed a benchmark concentration. In addition, trends in indicator concentrations are also examined throughout the storm drain network.

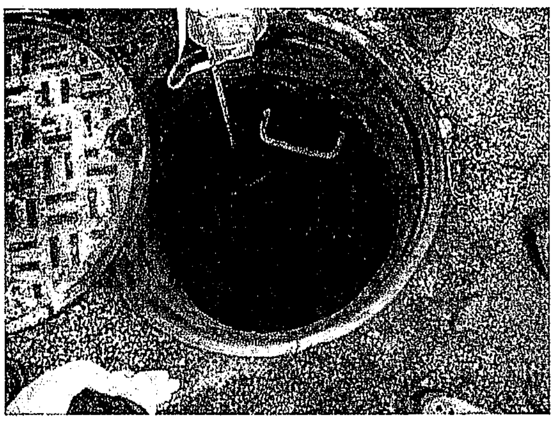

**Figure 56: Techniques to Sample from the Storm Drain**

Figure 57 profiles a storm drain network investigation that used ammonia as the indicator parameter and a benchmark concentration of 1.0 mg/L. At both the outfall and the first manhole up the trunk, field crews recorded finding "hits" for ammonia of 2.2 mg/L and 2.3 mg/L, respectively. Subsequent manhole inspections further up the network revealed one manhole with no flow, and a second with a hit for ammonia (2.4 mg/L). The crew then tracked the discharge upstream of the second manhole, and found a third manhole with a low ammonia reading (0.05 mg/L) and a fourth with a much higher reading (4.3 mg/L). The crew then redirected its effort to sample above the fourth manhole with the 4.3 mg/L concentration, only to find another low reading. Based on this pattern, the crew concluded the discharge source was located between these two manholes, as nothing else could explain this sudden increase in concentration over this length of pipe.

The results of storm drain network investigations should be systematically documented to guide future discharge investigations, and describe any infrastructure maintenance problems encountered. An example of a sample manhole inspection field log is displayed in Figure 58.

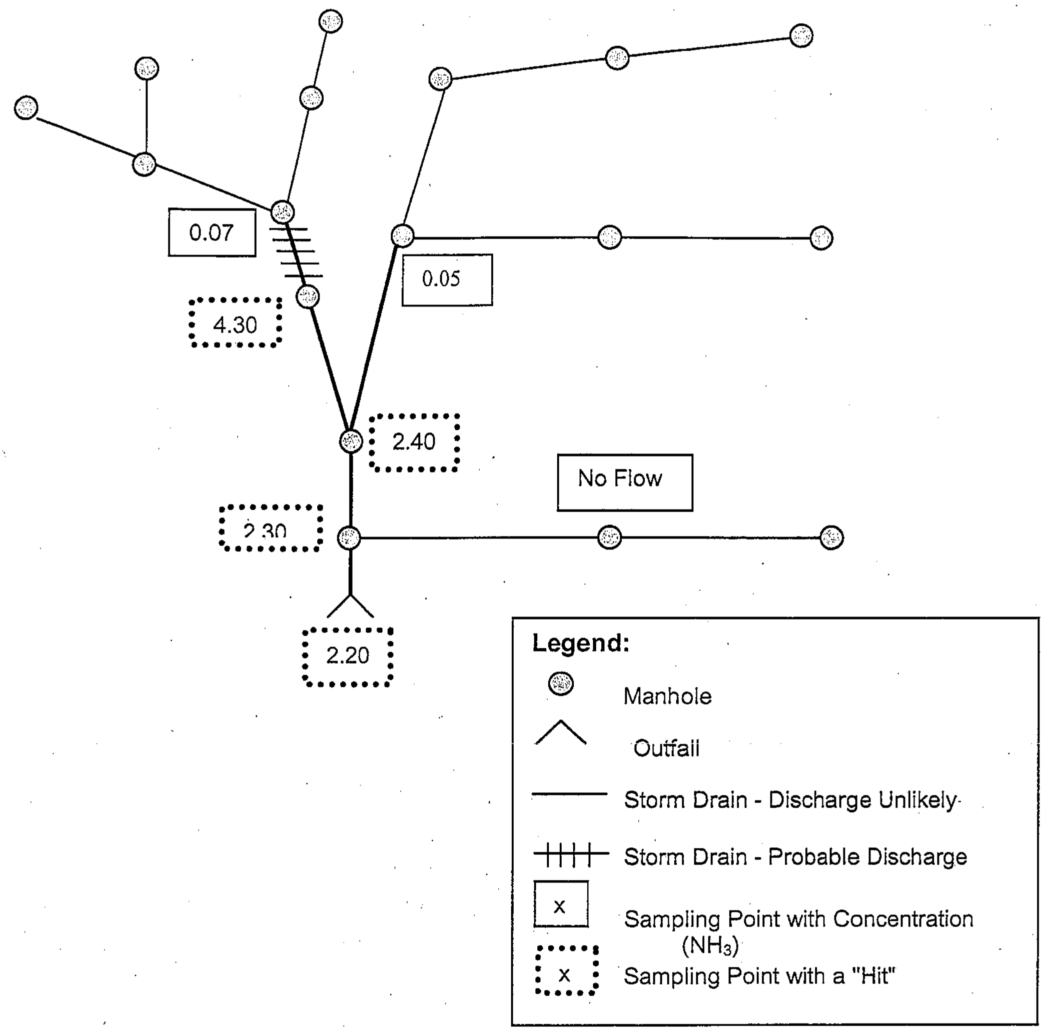


**Figure 57: Use of Ammonia as a Trace Parameter to Identify an Illicit Discharge**

**BOSTON WATER AND SEWER COMMISSION**
**MANHOLE INSPECTION LOG**

**Manhole ID No.** ____________

Inspection Date: ____________ Tributary Area: ____________

Street: ____________ Manhole Type:

Inspection: Not Found ___ Surface ___ Internal ___ Sanitary Sewer _____ Storm Drain _____

Follow Up Inspection ________ High Outlet _______ Lovejoy _______

Time Since Last Rain:

Inspector: ____________ < 48 hours ____ 48 – 72 hours ____ > 72 hours ____

**Observations:**

Standing Water in Manhole: Yes ____ No ____ Color of Water: Clear ____ Cloudy ____ Other ____________

Flow in Manhole: Yes _____ No _____ Velocity: Slow _____ Medium _____ Fast _____ Depth of Flow: _____ in.

Color of Flow: No Flow: _____ Clear _____ Cloudy _____ Suspended Solids _____ Other ____________

Blockages: Yes _____ No _____ Sediment in Manhole: Yes ____ No ____ If Yes: Percent of Pipe Filled: _____ %

Floatables: None _____ Sewage _____ Oily Sheen _____ Foam _____ Other ____________

Odor: None _____ Sewage _____ Oil _____ Soap _____ Other ____________

**Field Testing:**

pH _____ Temp _____ Spec. Cond. _____ Surfactants: Yes _____ No __ Ammonia: Yes _____ No __

**Contamination:**

Found During Inspection Yes __ Check one: __Observation __Positive Test Kit Result

No __ Sandbagged Placed No __ Yes ___ Give Date ________

Sandbag Checked (Date): _______ Flow was ____Captured ____Not Captured:

**Condition of Manhole:** Common Manholes:

Grade: At _____ Above_____ Below _____ High Outlet: Blocked Yes ___ No ___ NA ___

Lovejoy: Cover Plate in Place Yes ___ No ___ NA ___

| | Good | Fair | Poor | Comments |
|---|---|---|---|---|
| Pavement | ___ | ___ | ___ | ________ |
| Cover | ___ | ___ | ___ | ________ |
| Frame | ___ | ___ | ___ | ________ |
| Corbel | ___ | ___ | ___ | ________ |
| Walls | ___ | ___ | ___ | ________ |
| Floor | ___ | ___ | ___ | ________ |

Construction Material:

| | Brick | Precast | Other |
|---|---|---|---|
| Corbel | ___ | ___ | ________ |
| Walls | ___ | ___ | ________ |
| Floor | ___ | ___ | ________ |

**Comments:** Manhole Correct as Mapped Yes _____ No _____ N↑

**Plan of Manhole**

**Figure 58: Boston Water and Sewer Commission Manhole Inspection Log (Source: Jewell, 2001)**

### *Methods to isolate intermittent discharges in the storm drain network*

Intermittent discharges are often challenging to trace in the storm drain network, although four techniques have been used with some success.

#### Sandbags

This technique involves placement of sandbags or similar barriers within strategic manholes in the storm drain network to form a temporary dam that collects any intermittent flows that may occur. Any flow collected behind the sandbag is then assessed using visual observations or by indicator sampling. Sandbags are lowered on a rope through the manhole to form a dam along the bottom of the storm drain, taking care not to fully block the pipe (in case it rains before the sandbag is retrieved). Sandbags are typically installed at junctions in the network to eliminate contributing branches from further consideration (Figure 59). If no flow collects behind the sandbag, the upstream pipe network can be ruled out as a source of the intermittent discharge.

Sandbags are typically left in place for no more than 48 hours, and should only be installed when dry weather is forecast. Sandbags should not be left in place during a heavy rainstorm. They may cause a blockage in the storm drain, or, they may be washed downstream and lost. The biggest downside to sandbagging is that it requires at least two trips to each manhole.

#### Optical Brightener Monitoring (OBM) Traps

Optical brightener monitoring (OBM) traps, profiled in Chapter 12, can also be used to detect intermittent flows at manhole junctions. When these absorbent pads are anchored in the pipe to capture dry weather flows, they can be used to determine the presence of flow and/or detergents. These OBM traps are frequently installed by lowering them into an open-grate drop inlet or storm drain inlet, as shown in Figure 60.The pads are then retrieved after 48 hours and are observed under a fluorescent light (this method is most reliable for undiluted washwaters).

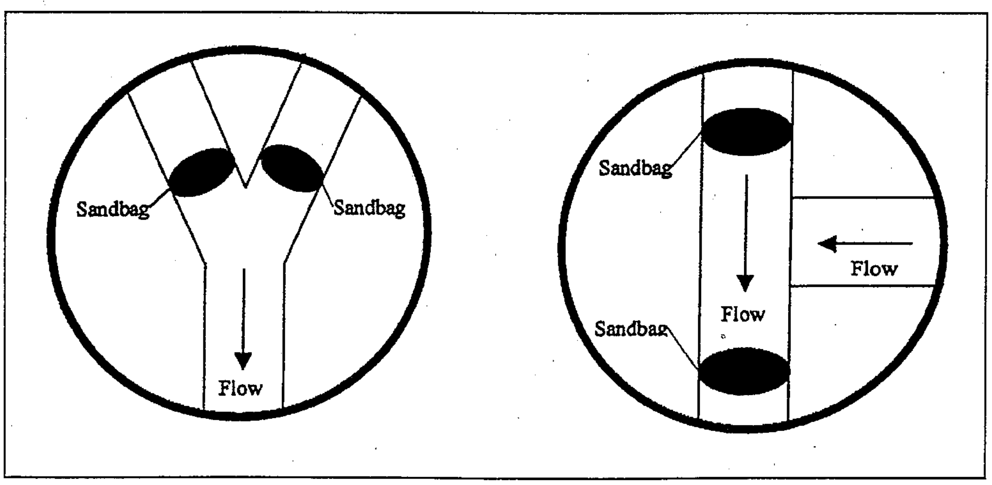


**Figure 59: Example Sandbag Placement (Source: Jewell, 2001)**

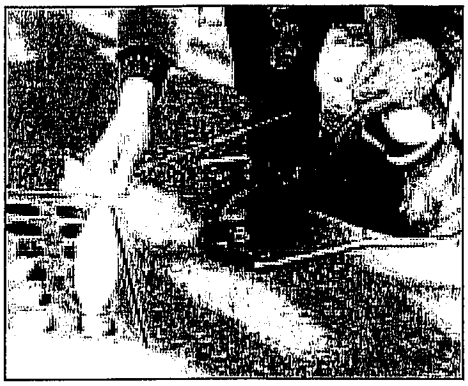

**Figure 60: Optical Brightener Placement in the Storm Drain**
*(Source: Sargent and Castonguay, 1998)*

Automatic Samplers
A few communities have installed automated samplers at strategic points within the storm drain network system that are triggered by small dry weather flows and collect water quality samples of intermittent discharges. Automated sampling can be extremely expensive, and is primarily used in very complex drainage areas that have severe intermittent discharge problems. Automated samplers can pinpoint the specific date and hours when discharges occur, and characterize its chemical composition, which can help crews fingerprint the generating source.

Observation of Deposits or Stains
Intermittent discharges often leave deposits or stains within the storm drain pipe or manhole after they have passed. Thus, crews should note whether any deposits or stains are present in the manhole, even if no dry weather flow is observed. In some cases, the origin of the discharge can be surmised by collecting indicator samples in the water ponded within the manhole sump. Stains and deposits, however, are not always a conclusive way to trace intermittent discharges in the storm drain network.

## 13.2 Drainage Area Investigations

The source of some illicit discharges can be determined through a survey or analysis of the drainage area of the problem outfall. The simplest approach is a rapid windshield survey of the drainage area to find the potential discharger or generating sites. A more sophisticated approach relies on an analysis of available GIS data and permit databases to identify industrial or other generating sites. In both cases, drainage area investigations are only effective if the discharge observed at an outfall has distinct or unique characteristics that allow crews to quickly ascertain the probable operation or business that is generating it. Often, discharges with a unique color, smell, or off-the-chart indicator sample reading may point to a specific industrial or commercial source. Drainage area investigations are not helpful in tracing sewage discharges, since they are often not always related to specific land uses or generating sites.

*Rapid Windshield Survey*

A rapid drive-by survey works well in small drainage areas, particularly if field crews are already familiar with its business operations. Field crews try to match the characteristics of the discharge to the most likely type of generating site, and then inspect all of the sites of the same type within the drainage area until the culprit is found. For example, if fuel is observed at an outfall, crews might quickly check every business operation in the catchment that stores or dispenses fuel. Another example is illustrated in Figure 61 where extremely dense algal growth was observed in a small stream during the winter. Field crews were aware of a fertilizer storage site in the drainage area, and a quick inspection identified it as the culprit.

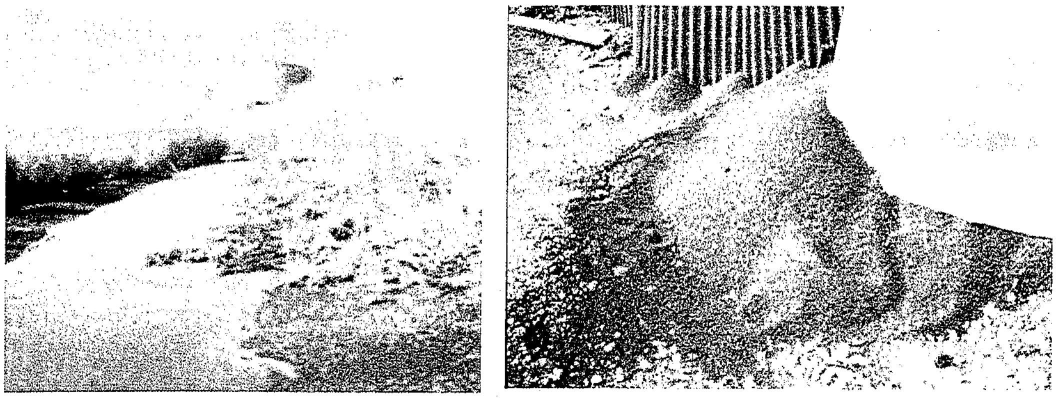

**Figure 61: Symptom (left): Extreme algal growth; Diagnosis (right): Cracked fertilizer storage is the phosphorus source**

A third example of the windshield survey approach is shown in Figure 62, where a very thick, sudsy and fragrant discharge was noted at a small outfall. The discharge appeared to consist of wash water, and the only commercial laundromat found upstream was confirmed to be the source. On-site testing may still be needed to identify the specific plumbing or connection generating the discharge.

### *Detailed Drainage Area Investigations*

In larger or more complex drainage areas, GIS data can be analyzed to pinpoint the source of a discharge. If only general land use data exist, maps can at least highlight suspected industrial areas. If more detailed SIC code data are available digitally, the GIS can be used to pull up specific hotspot operations or generating sites that could be potential dischargers. Some of the key discharge indicators that are associated with hotspots and specific industries are reviewed in Appendix K.

## 13.3 On-site Investigations

On-site investigations are used to pinpoint the exact source or connection producing a discharge within the storm drain network. The three basic approaches are dye, video and smoke testing. While each approach can determine the actual source of a discharge, each needs to be applied under the right conditions and test limitations (see Table 56). It should be noted that on-site investigations are not particularly effective in finding *indirect* discharges to the storm drain network.


**Figure 62: The sudsy, fragrant discharge (left) indicates that the laundromat is the more likely culprit than the florist (right).**

**Table 56: Techniques to Locate the Discharge**

| Technique | Best Applications | Limitations |
|---|---|---|
| Dye Testing | • Discharge limited to a very small drainage area (<10 properties is ideal)<br>• Discharge probably caused by a connection from an individual property<br>• Commercial or industrial land use | • May be difficult to gain access to some properties |
| Video Testing | • Continuous discharges<br>• Discharge limited to a single pipe segment<br>• Communities who own equipment for other investigations | • Relatively expensive equipment<br>• Cannot capture non-flowing discharges<br>• Often cannot capture discharges from pipes submerged in the storm drain |
| Smoke Testing | • Cross-connection with the sanitary sewer<br>• Identifying other underground sources (e.g., leaking storage techniques) caused by damage to the storm drain | • Poor notification to public can cause alarm<br>• Cannot detect all illicit discharges |

**TIP**

The Wayne County Department of the Environment provides excellent training materials on on-site investigations, as well as other illicit discharge techniques. More information about this training can be accessed from their website: Http://www.wcdoe.org/Watershed/Programs___Srvcs_/IDEP/idep.htm.

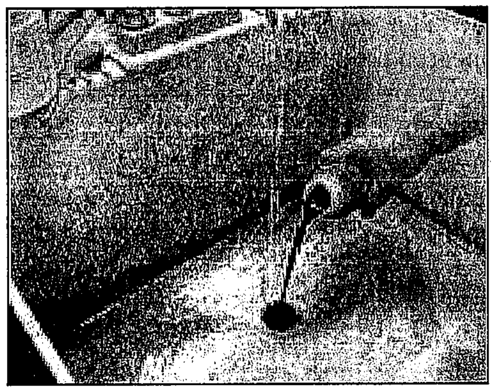

**Figure 63: Dye Testing Plumbing (NIWPC, 2003)**

*Dye Testing*

Dye testing is an excellent indicator of illicit connections and is conducted by introducing non-toxic dye into toilets, sinks, shop drains and other plumbing fixtures (see Figure 63). The discovery of dye in the storm drain, rather than the sanitary sewer, conclusively determines that the illicit connection exists.

Before commencing dye tests, crews should review storm drain and sewer maps to identify lateral sewer connections and how they can be accessed. In addition, property owners must be notified to obtain entry permission. For industrial or commercial properties, crews should carry a letter to document their legal authority to gain access to the property. If time permits, the letter can be sent in advance of the dye testing. For residential properties, communication can be more challenging. Unlike commercial properties, crews are not guaranteed access to homes, and should call ahead to ensure that the owner will be home on the day of testing.

Communication with other local agencies is also important since any dye released to the storm drain could be mistaken for a spill or pollution episode. To avoid a costly and embarrassing response to a false alarm, crews should contact key spill response agencies using a "quick fax" that describes when and where dye testing is occurring (Tuomari and Thomson, 2002). In addition, crews should carry a list of phone numbers to call spill response agencies in the event dye is released to a stream.

At least two staff are needed to conduct dye tests – one to flush dye down the plumbing fixtures and one to look for dye in the downstream manhole(s). In some cases, three staff may be preferred, with two staff entering the private residence or building for both safety and liability purposes.

The basic equipment to conduct dye tests is listed in Table 57 and is not highly specialized. Often, the key choice is the type of dye to use for testing. Several options are profiled in Table 58. In most cases, liquid dye is used, although solid dye tablets can also be placed in a mesh bag and lowered into the manhole on a rope (Figure 64).

| **Table 57: Key Field Equipment for Dye Testing** *(Source: Wayne County, MI, 2000)* |
|---|
| <u>Maps, Documents</u><br>• Sewer and storm drain maps (sufficient detail to locate manholes)<br>• Site plan and building diagram<br>• Letter describing the investigation<br>• Identification (e.g., badge or ID card)<br>• Educational materials (to supplement pollution prevention efforts)<br>• List of agencies to contact if the dye discharges to a stream.<br>• Name of contact at the facility |
| <u>Equipment to Find and Lift the Manhole Safely (small manhole often in a lawn)</u><br>• Probe<br>• Metal detector<br>• Crow bar<br>• Safety equipment (hard hats, eye protection, gloves, safety vests, steel-toed boots, traffic control equipment, protective clothing, gas monitor) |
| <u>Equipment for Actual Dye Testing and Communications</u><br>• 2-way radio<br>• Dye (liquid or "test strips")<br>• High powered lamps or flashlights<br>• Water hoses<br>• Camera |

**Figure 64: Dye in a mesh bag is placed into an upstream manhole (left); Dye observed at a downstream manhole traces the path of the storm drain (right)**



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If a longer pipe network is being tested, and dye is not expected to appear for several hours, charcoal packets can be used to detect the dye (GCHD, 2002). Charcoal packets can be secured and left in place for a week or two, and then analyzed for the presence of dye. Instructions for using charcoal packets in dye testing can be accessed at the following website: http://bayinfo.tamug.tamu.edu/gbeppubs/ms4.pdf.

The basic drill for dye tests consists of three simple steps. First, flush or wash dye down the drain, fixture or manhole. Second, pop open downgradient sanitary sewer manholes and check to see if any dye appears. If none is detected in the sewer manhole after an hour or so, check downgradient storm drain manholes or outfalls for the presence of dye. Although dye testing is fairly straightforward, some tips to make testing go more smoothly are offered in Table 59.

**Table 58: Dye Testing Options**

| Product | Applications |
|---|---|
| Dye Tablets | • Compressed powder, useful for releasing dye over time<br>• Less messy than powder form<br>• Easy to handle, no mess, quick dissolve<br>• Flow mapping and tracing in storm and sewer drains<br>• Plumbing system tracing<br>• Septic system analysis<br>• Leak detection |
| Liquid Concentrate | • Very concentrated, disperses quickly<br>• Works well in all volumes of flow<br>• Recommended when metering of input is required<br>• Flow mapping and tracing in storm and sewer drains<br>• Plumbing system tracing<br>• Septic system analysis<br>• Leak detection |
| Dye Strips | • Similar to liquid but less messy |
| Powder | • Can be very messy and must dissolve in liquid to reach full potential<br>• Recommended for very small applications or for very large applications where liquid is undesirable<br>• Leak detection |
| Dye Wax Cakes | • Recommended for moderate-sized bodies of water<br>• Flow mapping and tracing in storm and sewer drains |
| Dye Wax Donuts | • Recommended for large sized bodies of water (lakes, rivers, ponds)<br>• Flow mapping and tracing in storm and sewer drains<br>• Leak detection |

**Table 59: Tips for Successful Dye Testing**
***(Adapted from Tuomari and Thompson, 2002)***

Dye Selection
- Green and liquid dyes are the easiest to see.
- Dye test strips can be a good alternative for residential or some commercial applications. (Liquid can leave a permanent stain).
- Check the sanitary sewer before using dyes to get a "base color." In some cases, (e.g., a print shop with a permitted discharge to the sanitary sewer), the sewage may have an existing color that would mask a dye.
- Choose two dye colors, and alternate between them when testing multiple fixtures.

Selecting Fixtures to Test
- Check the plumbing plan for the site to isolate fixtures that are separately connected.
- For industrial facilities, check most floor drains (these are often misdirected).
- For plumbing fixtures, test a representative fixture (e.g., a bathroom sink).
- Test some locations separately (e.g., washing machines and floor drains), which may be misdirected.
- If conducting dye investigations on multiple floors, start from the basement and work your way up.
- At all fixtures, make sure to flush with plenty of water to ensure that the dye moves through the system.

Selecting a Sewer Manhole for Observations
- Pick the closest manhole possible to make observations (typically a sewer lateral).
- If this is not possible, choose the nearest downstream manhole.

Communications Between Crew Members
- The individual conducting the dye testing calls in to the field person to report the color dye used, and when it is dropped into the system.
- The field person then calls back when dye is observed in the manhole.
- If dye is not observed (e.g., after two separate flushes have occurred), dye testing is halted until the dye appears.

Locating Missing Dye
- The investigation is not complete until the dye is found. Some reasons for dye not appearing include:
- The building is actually hooked up to a septic system.
- The sewer line is clogged.
- There is a leak in the sewer line or lateral pipe.

## *Video Testing*

Video testing works by guiding a mobile video camera through the storm drain pipe to locate the actual connection producing an illicit discharge. Video testing shows flows and leaks within the pipe that may indicate an illicit discharge, and can show cracks and other pipe damage that enable sewage or contaminated water to flow into the storm drain pipe.

Video testing is useful when access to properties is constrained, such as residential neighborhoods. Video testing can also be expensive, unless the community already owns and uses the equipment for sewer inspections. This technique will not detect all types of discharges, particularly when the illicit connection is not flowing at the time of the video survey.

Different types of video camera equipment are used, depending on the diameter and condition of the storm sewer being tested.

Field crews should review storm drain maps, and preferably visit the site before selecting the video equipment for the test. A field visit helps determine the camera size needed to fit into the pipe, and if the storm drain has standing water.

In addition to standard safety equipment required for all manhole inspections, video testing requires a Closed-Circuit Television (CCTV) and supporting items. Many commercially available camera systems are specifically adapted to televise storm sewers, ranging from large truck or van-mounted systems to much smaller portable cameras. Cameras can be self-propelled or towed. Some specifications to look for include:

- The camera should be capable of radial view for inspection of the top, bottom, and sides of the pipe and for looking up lateral connections.
- The camera should be color.
- Lighting should be supplied by a lamp on the camera that can light the entire periphery of the pipe.

When inspecting the storm sewer, the CCTV is oriented to keep the lens as close as possible to the center of the pipe. The camera can be self-propelled through the pipe using a tractor or crawler unit or it may be towed through on a skid unit (see Figures 65 and 66). If the storm drain has ponded water, the camera should be attached to a raft, which floats through the storm sewer from one manhole to the next. To see details of the sewer, the camera and lights should be able to swivel both horizontally and vertically. A video record of the inspection should be made for future reference and repairs (see Figure 67).

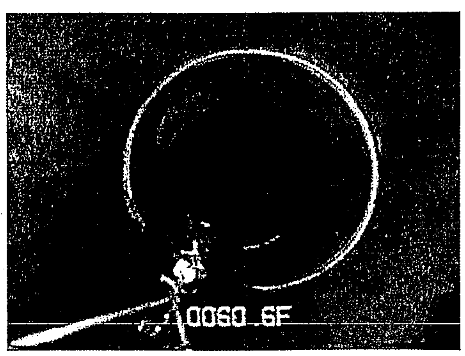

**Figure 65: Camera being towed**

### *Smoke Testing*

Smoke testing is another "bottom up" approach to isolate illicit discharges. It works by introducing smoke into the storm drain system and observing where the smoke surfaces. The use of smoke testing to detect illicit discharges is a relatively new application, although many communities have used it to check for infiltration and inflow into their sanitary sewer network. Smoke testing can find improper connections, or damage to the storm drain

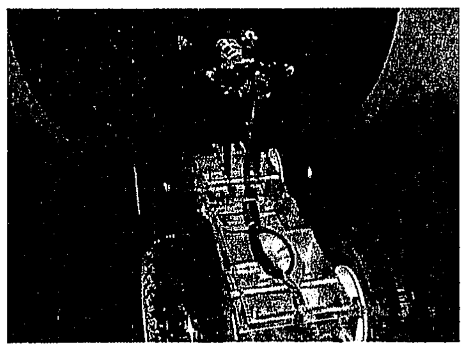

**Figure 66: Tractor-mounted Camera**

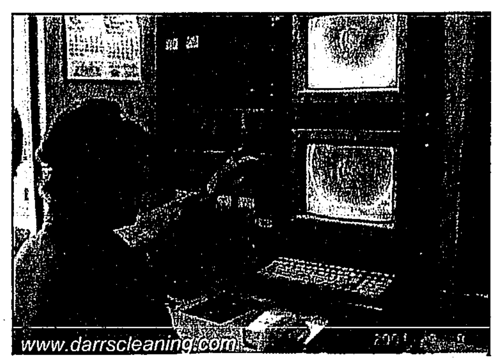


**Figure 67: Review of an Inspection Video**



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system (Figure 68). This technique works best when the discharge is confined to the upper reaches of the storm drain network, where pipe diameters are to small for video testing and gaining access to multiple properties renders dye testing infeasible.

Notifying the public about the date and purpose of smoke testing before starting is critical. The smoke used is non-toxic, but can cause respiratory irritation, which can be a problem for some residents. Residents should be notified at least two weeks prior to testing, and should be provided the following information (Hurco Technologies, Inc., 2003):

- Date testing will occur
- Reason for smoke testing
- Precautions they can take to prevent smoke from entering their homes or businesses
- What they need to do if smoke enters their home or business, and any health concerns associated with the smoke
- A number residents can call to relay any particular health concerns (e.g., chronic respiratory problems)

Program managers should also notify local media to get the word out if extensive smoke testing is planned (e.g., television, newspaper, and radio). On the actual day of testing, local fire, police departments and 911 call centers should be notified to handle any calls from the public (Hurco Technologies, Inc., 2003).

The basic equipment needed for smoke testing includes manhole safety equipment, a smoke source, smoke blower, and sewer plugs. Two smoke sources can be used for smoke testing. The first is a smoke "bomb," or "candle" that burns at a controlled rate and releases very white smoke visible at relatively low concentrations (Figure 69). Smoke bombs are suspended beneath a blower in a manhole. Candles are available in 30 second to three minute sizes. Once opened, smoke bombs should be kept in a dry location and should be used within one year.

The second smoke source is liquid smoke, which is a petroleum-based product that is injected into the hot exhaust of a blower where it is heated and vaporized (Figure 70). The length of smoke production can vary depending on the length of the pipe being tested. In general, liquid smoke is not as consistently visible and does not travel as far as smoke from bombs (USA Blue Book).

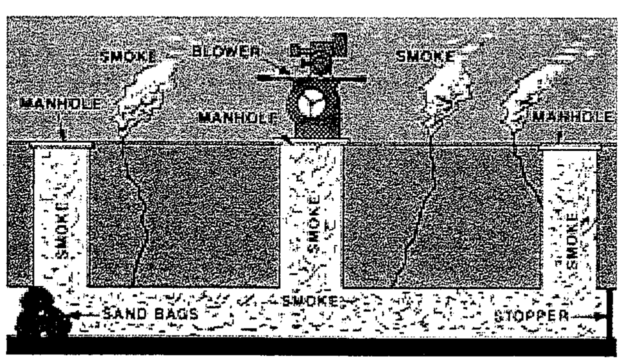


Figure 68: Smoke Testing System Schematic

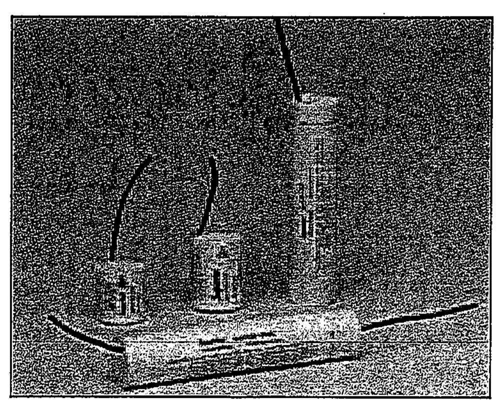

Figure 69: Smoke Candles



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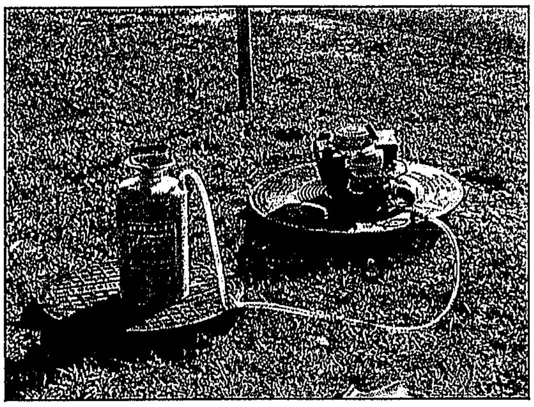

**Figure 70: Smoke Blower**

Smoke blowers provide a high volume of air that forces smoke through the storm drain pipe. Two types of blowers are commonly used: "squirrel cage" blowers and direct-drive propeller blowers. Squirrel cage blowers are large and may weigh more than 100 pounds, but allow the operator to generate more controlled smoke output. Direct-drive propeller blowers are considerably lighter and more compact, which allows for easier transport and positioning.

Three basic steps are involved in smoke testing. First, the storm drain is sealed off by plugging storm drain inlets. Next, the smoke is released and forced by the blower through the storm drain system. Lastly, the crew looks for any escape of smoke above-ground to find potential leaks.

One of three methods can be used to seal off the storm drain. Sandbags can be lowered into place with a rope from the street surface. Alternatively, beach balls that have a diameter slightly larger than the drain can be inserted into the pipe. The beach ball is then placed in a mesh bag with a rope attached to it so it can be secured and retrieved. If the beach ball gets stuck in the pipe, it can simply be punctured, deflated and removed. Finally, expandable plugs are available, and may be inserted from the ground surface.

Blowers should be set up next to the open manhole after the smoke is started. Only one manhole is tested at a time. If smoke candles are used, crews simply light the candle, place it in a bucket, and lower it in the manhole. The crew then watches to see where smoke escapes from the pipe. The two most common situations that indicate an illicit discharge are when smoke is seen rising from internal plumbing fixtures (typically reported by residents) or from sewer vents (Figure 71). Sewer vents extend upward from the sewer lateral to release gas buildup, and are not supposed to be connected to the storm drain system.

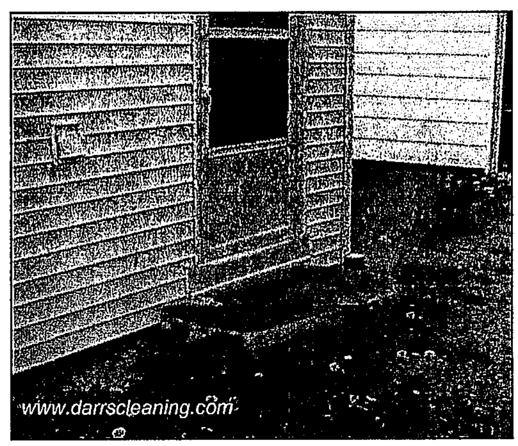


**Figure 71: Smoke Rising from Sewer Vent**

## 13.4 Septic System Investigations

The techniques for tracing illicit discharges are different in rural or low-density residential watersheds. Often, these watersheds lack sanitary sewer service and storm water is conveyed through ditches or swales, rather than enclosed pipes. Consequently, many illicit discharges enter the stream as indirect discharges, through surface breakouts of septic fields or through straight pipe discharges from bypassed septic systems.

The two broad techniques used to find individual septic systems -- on-site investigations and infrared imagery – are described in this section.

### *On-Site Septic Investigations*

Three kinds of on-site investigations can be performed at individual properties to determine if the septic system is failing, including homeowner survey, surface condition analysis and a detailed system inspection. The first two investigations are rapid and relatively simple assessments typically conducted in targeted watershed areas. Detailed system inspections are a much more thorough investigation of the functioning of the septic system that is conducted by a certified professional. Detailed system inspections may occur at time of sale of a property, or be triggered by poor scores on the rapid homeowner survey or surface condition analysis.

#### Homeowner Survey

The homeowner survey consists of a brief interview with the property owner to determine the potential for current or future failure of the septic system, and is often done in conjunction with a surface condition analysis.

Table 60 highlights some common questions to ask in the survey, which inquire about resident behaviors, system performance and maintenance activity.

#### Surface Condition Analysis

The surface condition analysis is a rapid site assessment where field crews look for obvious indicators that point to current or potential production of illicit discharges by the septic system (Figure 72). Some of the key surface conditions to analyze have been described by Andrews *et al.*, (1997) and are described below:

- Foul odors in the yard
- Wet, spongy ground; lush plant growth; or burnt grass near the drain field
- Algal blooms or excessive weed growth in adjacent ditches, ponds and streams
- Shrubs or trees with root damage within 10 feet of the system
- Cars, boats, or other heavy objects located over the field that could crush lateral pipes
- Storm water flowing over the drain field
- Cave-ins or exposed system components
- Visible liquid on the surface of the drain field (e.g., surface breakouts)
- Obvious system bypasses (e.g., straight pipe discharges)

| **Table 60: Septic System Homeowner Survey Questions** *(Adapted from Andrews et al., 1997 and Holmes Inspection Services)* |
|---|
| • How many people live in the house?[1]<br>• What is the septic tank capacity?[2]<br>• Do drains in the house empty slowly or not at all?<br>• When was the last time the system was inspected or maintained?<br>• Does sewage back up into the house through drain lines?<br>• Are there any wet, smelly spots in the yard?<br>• Is the septic tank effluent piped so it drains to a road ditch, a storm sewer, a stream, or is it connected to a farm drain tile? |
| [1] Water usage ranges from 50 to 100 gallons per day per person. This information can be used to estimate the wastewater load from the house (Andrews *et. al*, 1997).<br>[2] The septic tank should be large enough to hold two days' worth of wastewater (Andrews *et. al*, 1997). |

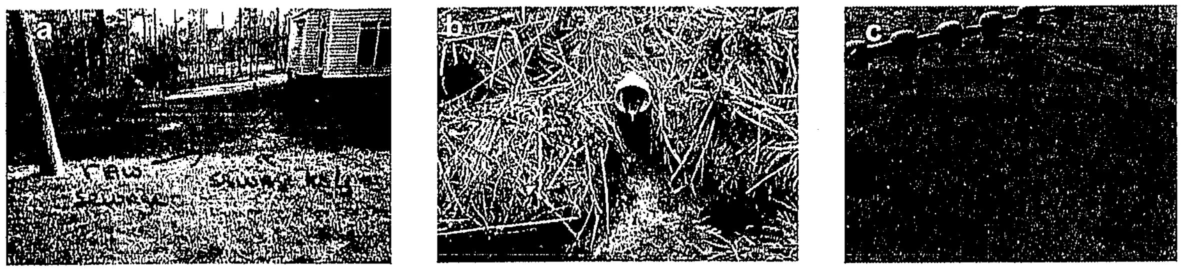

**Figure 72: (a) Wet, spongy ground. Grass may be bright green or burnt due to high nutrient loading. (b) Straight pipe discharge to nearby stream. (c) Algal bloom in a nearby pond.**
*(Sources: a- Anish Jantrania; b- Snohomish County, WA c- King County, WA)*

### Detailed System Inspection

The detailed system inspection is a much more thorough inspection of the performance and function of the septic system, and must be completed by a certified professional. The inspector certifies the structural integrity of all components of the system, and checks the depth of solids in the septic tank to determine if the system needs to be pumped out. The inspector also sketches the system, and estimates distance to groundwater, surface water, and drinking water sources. An example septic system inspection form from Massachusetts can be found at http://www.state.ma.us/dep/brp/wwm/soilsys.htm.

Although not always incorporated into the inspection, dye testing can sometimes point to leaks from broken pipes, or direct discharges through straight pipes that might be missed during routine inspection. Dye can be introduced into plumbing fixtures in the home, and flushed with sufficient running water. The inspector then watches the septic field, nearby ditches, watercourses and manholes for any signs of the dye (Figure 73). The dye may take several hours to appear, so crews may want to place charcoal packets in adjacent waters to capture dye until they can return later to retrieve them.

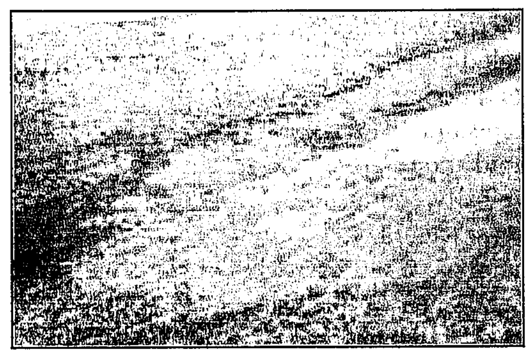

**Figure 73: Dye surfacing in a septic field**

### Infrared Imagery

Infrared imagery is a special type of photography with gray or color scales that represent differences in temperature and emissivity of objects in the image (www.stocktoninfrared.com), and can be used to locate sewage discharges. Several different infrared imagery techniques can be used to identify illicit discharges. The following discussion highlights two of these: aerial infrared thermography[13] and color infrared aerial photography.

#### Infrared Thermography

Infrared thermography is increasingly being used to detect illicit discharges and failing septic systems. The technique uses the

[13] Infrared thermography is also being used by communities such as Mecklenburg County and the City of Charlotte in NC to detect illicit discharges at outfalls.

temperature difference of sewage as a marker to locate these illicit discharges. Figure 74 illustrates the thermal difference between an outfall discharge (with a higher temperature) and a stream.

The equipment needed to conduct aerial infrared thermography includes an aircraft (plane or helicopter); a high-resolution, large format, infrared camera with appropriate mount; a GPS unit; and digital recording equipment. If a plane is used, a higher resolution camera is required since it must operate at higher altitudes. Pilots should be experienced since flights take place at night, slowly, and at a low altitude. The camera may be handheld, but a mounted camera will provide significantly clearer results for a larger area. The GPS can be combined with a mobile mapping program and a video encoder-decoder that encodes and displays the coordinates, date, and time (Stockton, 2000). The infrared data are analyzed after the flight by trained analysts to locate suspected discharges, and field crews then inspect the ground-truthed sites to confirm the presence of a failing septic system.

Late fall, winter, and early spring are typically the best times of year to conduct these investigations in most regions of the country. This allows for a bigger difference between receiving water and discharge temperatures, and interference from vegetation is minimized (Stockton, 2004b). In addition, flights should take place at night to minimize reflected and direct daylight solar radiation that may adversely affect the imagery (Stockton, 2004b).


**Figure 74: Aerial Thermography Showing Sewage Leak**

## Color Infrared Aerial Photography

Color infrared aerial photography looks for changes in plant growth, differences in soil moisture content, and the presence of standing water on the ground to primarily identify failing septic systems (Figure 75).

The Tennessee Valley Authority (TVA) uses color infrared aerial photography to detect failing septic systems in reservoir watersheds. Local health departments conduct follow-up ground-truthing surveys to determine if a system is actually failing (Sagona, 1986). Similar to thermography, it is recommended that flights take place at night, during leaf-off conditions, or when the water table is at a seasonal high (which is when most failures typically occur (U.S. EPA, 1999).

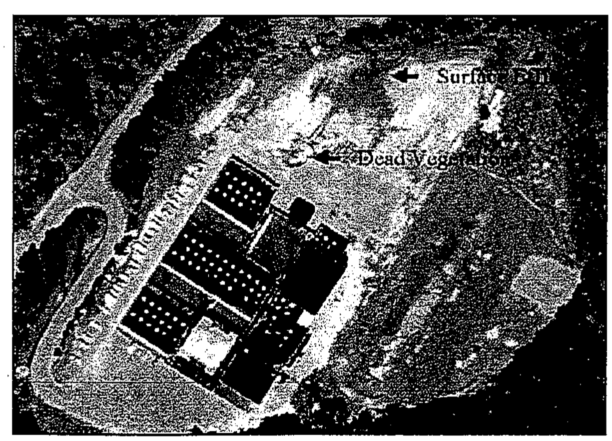

**Figure 75: Dead vegetation and surface effluent are evidence of a septic system surface failure.**
*(Source: U.S. EPA, 1999)*

## 13.5 The Cost to Trace Illicit Discharge Sources

Tracing illicit discharges to their source can be an elusive and complex process, and precise staffing and budget data are difficult to estimate. Experience of Phase I NPDES communities that have done these investigations in the past can shed some light on cost estimates. Some details on unit costs for common illicit discharge investigations are provided below.

### *Costs for Dye, Video, and Smoke Testing*

The cost of smoke, dye, and video testing can be substantial and staff intensive, and often depend on investigation specific factors, such as the complexity of the drainage network, density and age of buildings, and complexity of land use. Wayne County, MI, has estimated the cost of dye testing at $900 per facility. Video testing costs range from $1.50 to $2.00 per foot, although this increases by $1.00 per foot if pipe cleaning is needed prior to testing.

Table 61 summarizes the costs of start-up equipment for basic manhole entry and inspection, which is needed regardless of which type of test is performed. Tables 62 through 64 provide specific equipment costs for dye, video and smoke testing, respectively.

**Table 61: Common Field Equipment Needed for Dye, Video, and SmokeTesting**

| Item | Cost |
|---|---|
| 1 Digital Camera | $200 |
| Clipboards, Pens, Batteries | $25 |
| 1 Field vehicle | $15,000 - $35,000 |
| 1 First aid kit | $30 |
| 1 Spotlight | $40 |
| 1 Gas monitor and probe | $900 - $2,100 |
| 1 Hand-held GPS Unit | $150 |
| 2 Two-way radios | $250 - $750 |
| 1 Manhole hook | $80 - $130 |
| 1 Mirror | $70 - $130 |
| 2 Reflective safety vests | $40 |
| Rubber/latex gloves (box of 100) | $25 |
| 1 Can of Spray Paint | $5 |
| 4 Traffic Cones | $50 |

| Table 62: Equipment Costs for Dye Testing | | |
|---|---|---|
| **Product** | **Water Volume** | **Cost** |
| Dye Strips | 1 strip / 500 gallons | $75 - $94 per 100 strips |
| Dye Tablets | 0 – 50,000 gallons | $40 per 200 tablets |
| Liquid Concentrate (Rhodamine WT) | 0 – 50,000 gallons | $80 - $90 per gallon<br>$15 - $20 per pint |
| Powder | 50,000 + gallons | $77 per lb |
| Dye Wax Cakes | 20,000 – 50,000 gallons | $12 per one 1.25 ounce cake |
| Dye Wax Donuts | 50,000 + gallons | $104 - $132 per 42 oz. donut |
| *Price Sources:*<br>*Aquatic Eco-Systems http://www.aquaticeco.com/*<br>*Cole Parmer http:/www.coleparmer.com*<br>*USA Blue Book http:/www.usabluebook.com* | | |

| Table 63: Equipment Costs for Video Testing | |
|---|---|
| **Equipment** | **Cost** |
| GEN-EYE 2™ B&W Sewer Camera with VCR & 200' Push Cable | $5,800 |
| 100' Push Rod and Reel Camera for 2" – 10" Pipes | $5,300 |
| 200' Push Rod and Reel Camera for 8" – 24" Pipes | $5,800 |
| Custom Saturn III Inspection System<br>500' cable for 6-16" Lines | $32,000<br>($33,000 with 1000 foot cable) |
| OUTPOST<br>• Box with build-out<br>• Generator<br>• Washdown system | $6,000<br>$2,000<br>$1,000 |
| Video Inspection Trailer<br>• 7'x10' trailer & build-out<br>• Hardware and software package<br>• Incidentals | $18,500<br>$15,000<br>$5,000 |
| Sprinter Chassis Inspection Vehicle<br>• Van (with build-out for inspecting 6" – 24" pipes)<br>• Crawler (needed to inspect pipes >24")<br>• Software upgrade (optional but helpful for extensive pipe systems) | $130,000<br>$18,000<br>$8,000 |
| *Sources: USA Blue Book and Envirotech* | |

| Table 64: Equipment Costs for Smoke Testing | |
|---|---|
| **Equipment** | **Cost** |
| Smoke Blower | $1,000 to $2,000 each |
| Liquid Smoke | $38 to $45 per gallon |
| Smoke Candles, 30 second (4,000 cubic feet) | $27.50 per dozen |
| Smoke Candles, 60 Second (8,000 cubic feet) | $30.50 per dozen |
| Smoke Candles, 3 Minute (40,000 cubic feet) | $60.00 per dozen |
| *Sources: Hurco Tech, 2003 and Cherne Industries, 2003* | |

### *Costs for Septic System Investigations*

Most septic system investigations are relatively low cost, but factors such as private property access, notification, and the total number of sites investigated can increase costs. Unit costs for the three major septic system investigations are described below.

#### Homeowner Survey and Surface Condition Analysis

Both the homeowner survey and the surface condition analysis are relatively low cost investigation techniques. Assuming that a staff person can investigate one home per hour, the average cost per inspection is approximately $25. A substantial cost savings can be realized by using interns or volunteers to conduct these simple investigations.

#### Detailed System Inspection

Septic system inspections are more expensive, but a typical unit cost is about $250, and may also include an additional cost of pumping the system, at roughly $150, if pumping is required to complete the inspection (Wayne County, 2003). This cost is typically charged to the homeowner as part of a home inspection.

#### Aerial Infrared Thermography

The equipment needed to conduct aerial infrared thermography is expensive; cameras alone may range from $250,000 to $500,000 (Stockton, 2004a). However, private contractors provide this service. In general, the cost to contract an aerial infrared thermography investigation depends on the length of the flight (flights typically follow streams or rivers); how difficult it will be to fly the route; the number of heat anomalies expected to be encountered; the expected post-flight processing time (typically, four to five hours of analysis for every hour flown); and the distance of the site from the plane's "home" (Stockton, 2004a). The cost range is typically $150 to $400 per mile of stream or river flown, which includes the flight and post-flight analyses (Stockton, 2004a).

As an alternative, local police departments may already own an infrared imaging system that may be used. For instance, the Arkansas Department of Health used a state police helicopter with a Forward Looking Infrared (FLIR) imaging system, GPS, video equipment, and maps (Eddy, 2000). The disadvantage to this is that the equipment may not be available at optimal times to conduct the investigation. In addition, infrared imaging equipment used by police departments may not be sensitive enough to detect the narrow range of temperature difference (only a few degrees) often expected for sewage flows (Stockton, 2004a).

# Chapter 14: Techniques to Fix Discharges

Quick and efficient correction of illicit discharges begins with having well defined legal authority and responsibilities coupled with strong enforcement and follow-up measures. Chapter 4 discussed important considerations with respect to legal authority and responsibility and Appendix B contains a model illicit discharge ordinance that provides language on violations, enforcement and penalties.

Most illicit discharge corrective actions involve some form of infrastructure modification or repair. These structural repairs are used to eliminate a wide variety of **direct discharges** such as sewage cross-connections, straight pipes, industrial cross-connections, and commercial cross-connections. Fixes range from simple plumbing projects to excavation and replacement of sewer lines. In some cases, structural repairs are necessary when **indirect** discharges, such as sewage from a sewer break or pump station failure enter the MS4 through an inlet, or flows directly into receiving waters. Most **transitory** discharges are corrected simply with spill containment and clean-up procedures. Section 8.3 previously discussed an overview of the correction process. The following section discusses more specific correction considerations.

## 14.1 Implementation Considerations

Once the source of an illicit discharge has been identified, steps should be taken to fix or eliminate the discharge. The following four questions should be answered for each individual illicit discharge to determine how to proceed:

- Who is responsible?
- What methods will be used to fix it?
- How long will it take?
- How will removal be confirmed?

The answer to each of these questions depends on the source of the discharge. Illicit discharges generally originate from one of the following sources:

- *An internal plumbing connection* (e.g., the discharge from a washing machine is directed to the building's storm lateral; the floor drain in a garage is connected to the building's storm lateral)
- *A service lateral cross-connection* (e.g., the sanitary lateral from a building is connected to the MS4)
- *An infrastructure failure within the sanitary sewer or MS4* (e.g., a collapsed sanitary line is discharging into the MS4)
- *An indirect transitory discharge resulting from leaks, spills, or overflows.*

Financial responsibility for source removal will typically fall on property owners, MS4 operators, or some combination of the two.

*Who's responsible for fixing the problem?*

Ultimate responsibility for removing the source of a discharge is generally that of either the property owner or the municipality/utility (e.g., primary owner/operator of the MS4).

### Internal Plumbing Connection

The responsibility for correcting an internal plumbing connection is generally the responsibility of the building owner. Communities may wish to develop a list of certified contractors that property owners can hire for corrections.

### Service Lateral

As with internal plumbing connections, the responsibility for correcting a problem within a service lateral is typically that of the property owner being served by the lateral. However, the cost of correcting a service lateral problem can be significantly higher than that of fixing an internal plumbing problem, so communities may want to consider alternative remedial approaches than those for internal plumbing corrections. For example, communities can have on-call contractors fix lateral connections allowing the problem to be fixed as soon as it is discovered. The community can then: 1) pay for correction costs through the capital budget, or state or federal funding options, or 2) share the cost with the owner, or 3) pass on the full cost to the property owner.

### Infrastructure Failure Within the Sanitary Sewer or MS4

Illicit discharges related to some sort of infrastructure failure within the sanitary sewer or MS4 should be corrected by the jurisdiction, utility, or agency responsible for maintenance of the sewers and drains.

### Transitory Discharge

Repair of transitory discharge sources will usually be the responsibility of the property owner where the discharge originates. Ordinances should clearly stipulate the time frame in which these discharges should be repaired.

*What methods will be used to fix the problem?*

The methods used to eliminate discharges will vary depending on the type of problem and the location of the problem. Internal plumbing corrections can often be performed using standard plumbing supplies for relatively little cost. For correction locations that occur outside of the building, such as service laterals or infrastructure in the right of way, costs tend to be significantly more due to specialized equipment needs. Certified contractors are recommended for these types of repairs. Table 65 provides a summary of a range of methods for fixing these more significant problems along with estimated costs. The last six techniques described in Table 68 are used for sanitary sewer line repair and rehabilitation. These activities are typically used when there is evidence of significant seepage from the sanitary system to the storm drain system.

*How long should it take?*

The timeframe for eliminating a connection or discharge should depend on the type of connection or discharge and how difficult elimination will be. A discharge that poses a significant threat to human or environmental health should be discontinued and eliminated immediately. Clear guidance should be provided in the local ordinance on the timeframe for removing discharges and connections. Typically, discharges should be stopped within seven days of notification by the municipality, and illicit connections should be repaired within 30 days of notification.

*How is the removal or correction confirmed?*

Removal and correction of a discharge or connection should be confirmed both at the source, to ensure that the correction has been made, and downstream, to ensure that it is the only local discharge present.

For discharges resulting from internal plumbing and lateral connections, dye testing can confirm the correction. Also, sandbagging should be done in the first accessible storm drain manhole downstream of the correction to verify that this was the only discharge present.

The correction of discharges resulting from some sort of infrastructure failure in the sanitary sewer or MS4 can be verified by dye testing or televising the line in conjunction with sandbagging and sampling at an accessible downstream manhole.

**Table 65: Methods to Eliminate Discharges**

| Technique | Application | Description | Estimated Cost |
|---|---|---|---|
| 1. Service Lateral Disconnection, Reconnection | Lateral is connected to the wrong line | Lateral is disconnected and reconnected to appropriate line | $2,500[1] |
| 2. Cleaning | Line is blocked or capacity diminished | Flushing (sending a high pressure water jet through the line); pigging (dragging a large rubber plug through the lines); or rodding | $1 / linear foot[2] |
| 3. Excavation and Replacement | Line is collapsed, severely blocked, significantly misaligned, or undersized | Existing pipe is removed, new pipe placed in same alignment; Existing pipe abandoned in place, replaced by new pipe in parallel alignment | For 14" line, $50-$100 / linear foot (higher number is associated with repaving or deeper excavations, if necessary)[2] |
| 4. Manhole Repair | Decrease ponding; prevent flow of surface water into manhole; prevent groundwater infiltration | Raise frame and lid above grade; install lid inserts; grout, mortar or apply shortcrete inside the walls; install new precast manhole. | Vary widely, from $250 to raise a frame and cover to ~ $2,000 to replace manhole[2] |
| 5. Corrosion Control Coating | Improve resistance to corrosion | Spray- or brush-on coating applied to interior of pipe. | < $10 / linear foot[2] |
| 6. Grouting | Seal leaking joints and small cracks | Seals leaking joints and small cracks. | For a 12" line, ~ $36-$54 / linear foot[2] |
| 7. Pipe Bursting | Line is collapsed, severely blocked, or undersized | Existing pipe used as guide for inserting expansion head; expansion head increases area available for new pipe by pushing existing pipe out radially until it cracks; bursting device pulls new pipeline behind it | For 8" pipe, $40-$80 / linear foot[4] |
| 8. Slip Lining | Pipe has numerous cracks, leaking joints, but is continuous and not misaligned | Pulling of a new pipe through the old one. | For 12" pipe, $50-$75 / linear foot[2] |
| 9. Fold and Formed Pipe | Pipe has numerous cracks, leaking joints | Similar to sliplining but is easier to install, uses existing manholes for insertion; a folded thermoplastic pipe is pulled into place and rounded to conform to internal diameter of existing pipe | For 8-12" pipe, $60-$78 / linear foot[3] |

| Table 65: Methods to Eliminate Discharges | | | |
|---|---|---|---|
| **Technique** | **Application** | **Description** | **Estimated Cost** |
| 10. Inversion Lining | Pipe has numerous cracks, leaking joints; can be used where there are misalignments | Similar to sliplining but is easier to install, uses existing manholes for insertion; a soft resin impregnated felt tube is inserted into the pipe, inverted by filling it with air or water at one end, and cured in place. | $75-$125 / linear foot[2] |
| [1] CWP (2002)<br>[2] 1991 costs from Brown (1995)<br>[3] U.S. EPA (1991)<br>[4] U.S. EPA (1999b) | | | |

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