DWR-1277

2005-23

Final Report

THE COST AND EFFECTIVENESS OF STORMWATER MANAGEMENT PRACTICES

Research

DWR-1277

Technical Report Documentation Page

1. Report No. MN/RC – 2005-23	2.	3. Recipients Accession No.
4. Title and Subtitle THE COST AND EFFECTIVENESS OF STORMWATER MANAGEMENT PRACTICES		5. Report Date June 2005 6.
7. Author(s) Peter T. Weiss, John S. Gulliver, Andrew J. Erickson		8. Performing Organization Report No.
9. Performing Organization Name and Address Department of Civil Engineering University of Minnesota 500 Pillsbury Drive SE Minneapolis, MN 55455		10. Project/Task/Work Unit No. 11. Contract (C) or Grant (G) No. (c) 81655 (wo) 78
12. Sponsoring Organization Name and Address Minnesota Department of Transportation Research Services Section 395 John Ireland Boulevard Mail Stop 330 St. Paul, Minnesota 55155		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code

15. Supplementary Notes

http://www.lrrb.org/pdf/200523.pdf

16. Abstract (Limit: 200 words)

Stormwater management practices for treating urban rainwater runoff were evaluated for cost and effectiveness in removing suspended sediments and phosphorus. Construction and annual operating and maintenance cost data was collected and analyzed for dry detention basins, wet basins, sand filters, constructed wetlands, bioretention filters, infiltration trenches, and swales using literature that reported on existing SMP sites across the United States. After statistical analysis on historical values of inflation and bond yields, the annual operating and maintenance costs were converted to a present worth based on a 20-year life and added to the construction cost. The total present cost of each SMP with the 67% confidence interval was reported as a function of the water quality design volume or, in the case of swales as a function of the swale top width, again with a 67% confidence interval. Finally, the mass of total suspended solids and total phosphorus removed over the 20-year life was estimated as a function of the water quality volume. The results can be used by planners and designers to estimate both the total cost of installing a stormwater management practice at a given site and the corresponding total suspended solids and phosphorus removal.

17. Document Analysis/Descriptors Stormwater Construction Constructed wetlands	Detention basins Sand filters Swales	18.Availability Statement No restrictions. Document available from: National Technical Information Services, Springfield, Virginia 22161	
19. Security Class (this report) Unclassified	20. Security Class (this page) Unclassified	21. No. of Pages 103	22. Price

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THE COST AND EFFECTIVENESS OF STORMWATER MANAGEMENT PRACTICES

Final Report

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June 2005

Published by:
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Executive Summary

Historical data has been used to compare the cost and effectiveness of several common stormwater management practices (SMP) including dry detention basins, wet detention basins, constructed wetlands, infiltration trenches, bioinfiltration filters, and sand filters. Data on construction costs and annual operating and maintenance costs have been combined to estimate the total present cost (TPC) of the SMPs in 2005 dollars as a function of water quality volume (WQV) or, in the case of swales, the swale top width. The TPC is based on 20 years of annual O&M costs which have been converted to a present value based on historical values of inflation and municipal bond yield rates.

The effectiveness of the SMPs as a function of WQV have been assessed by estimating the total amount of total suspended solids (TSS) and phosphorus (P) removed over a 20-year time period. Both the cost (*i.e.* TPC) and effectiveness (*i.e.* amount of TSS and P removed) estimates are presented with 67% confidence intervals. Also, in order to help the user incorporate land costs, typical land-area requirements for each SMP as a function of watershed area are presented.

For the six SMPs investigated, results show that, ignoring land costs, constructed wetlands are the least expensive to construct and maintain. However, since wetlands typically require more land area to be effective, land acquisition costs may result in wetlands being significantly more expensive then other SMPs that require less area. Also, the long-term capability of wetlands to remove phosphorus has been questioned by other authors.

The results presented in this report can be used by decision makers as a preliminary tool to compare SMPs in the categories of cost and impact on water quality. However, due to the wide

scatter in the original data, the confidence intervals associated with the estimates of TPC and amount of TSS and P removed also exhibit a relatively wide range.

Even with the scatter, the results can be used as a preliminary tool to compare SMPs which are under consideration for a given project.

For a more complete estimate of SMP cost and effectiveness, a more rigorous and detailed comparison which involves, as a minimum, a preliminary SMP design, should be performed.

Introduction

With the implementation of the United States Environmental Protection Agency's (USEPA) National Pollution Discharge Elimination Systems (NPDES) Phase I and II programs, strong interest has developed in the area of water quality treatment of stormwater runoff. While little is known about the cost effectiveness of available stormwater treatment technologies, called Stormwater Management Practices (SMPs) in this report, municipal agencies are now, or soon will be, required to meet certain pollutant removal criteria based on the Phase I and II regulations.

Of primary concern are nutrients such as phosphorus (P) and nitrogen (N), which are just one of the pollutant categories being targeted for removal from stormwater runoff. Excess nutrients can initiate large algae blooms that generate negative aesthetic and eutrophic conditions in receiving lakes and rivers (USEPA, 1999a). In inland water bodies phosphorus is typically the limiting nutrient (Schindler, 1977) and can be contributed to stormwater from various sources such as fertilizers, leaves, grass clippings, etc. (USEPA, 1999a). Another pollutant of primary concern in stormwater is dirt, sand, and other solid particles which are commonly quantified by measuring the Total Suspended Solids (TSS) of a water sample. TSS can severely and negatively impact an aquatic environment. The solids increase turbidity, inhibit plant growth and diversity, affect river biota and reduce the number of aquatic species (Shammaa *et al.*, 2002). Also, organic suspended solids can be biologically degraded by microorganisms in a process which consumes oxygen, which is important to the aquatic biota.

With total suspended solids and phosphorus a primary concern of most stormwater management plans, and with little known about the cost effectiveness of available stormwater treatment options, this report seeks to fill a need by developing both a cost-comparison tool (based on total construction cost not including land acquisition) and an effectiveness comparison tool (based on pounds of total suspended solids and phosphorus removed) for common SMPs. The method is based on published, credible information of existing SMPs relating to their construction and annual operating and maintenance (O&M) costs and their ability to remove TSS and P from stormwater runoff. The goal of the report is to provide planners and engineers with a pre-feasibility tool that can be used to compare the costs and impact on water quality of available SMPs.

Literature Review

Phosphorus can occur in both dissolved and particulate form in stormwater runoff. The dissolved fraction is often in the form of phosphates (PO_4^{3-}) (Jenkins *et al.*, 1971) which undergo hydrolysis in water to form H_3PO_4 (pH<2.16), $H_2PO_4^-$ (2.16 < pH < 7.20), HPO_4^{-2} (7.20 < pH < 12.35), or PO_4^{-3} (12.35 < pH). Dissolved phosphorus is usually and somewhat arbitrarily defined as that portion which can pass through a 0.45 micron filter. Solid or particulate phosphorus, defined as that portion which is retained by a 0.45 micron filter, can originate from grass clippings, leaves, animal waste or any other solid organic matter and may also be included as part of the TSS.

The Water Environment Federation in conjunction with the American Society of Civil Engineers (WEF and ASCE, 1998) site a USEPA (1983) publication that reports the expected event mean concentrations for total and dissolved phosphorus in urban runoff as 0.33 mg/L and 0.12 mg/L, respectively. A more recent report (Brown *et al.*, 2003) based upon three different studies that incorporated data from approximately 500, 107, and more than 3,783 storm events, respectively, claims that a total phosphorus concentration of 0.3 mg/L is adequate to describe both new and old urban development stormwater runoff. Brezonik and Stadelmann (2002) investigated urban runoff in the Twin Cities Metropolitan Area (Minneapolis and St. Paul, MN) and found that event mean concentrations for total and dissolved phosphorus varied as a function of climatic season as follows: 1.37 and 0.37 mg/L for winter, 0.85 and 0.53 mg/L for spring, 0.59 and 0.21 mg/L for summer, and 0.55 and 0.21 mg/L for fall. It must be noted that the values used to calculate average values often varied widely. Based on the wide scatter of data it can be concluded that phosphorus concentrations may vary widely both from site to site and at one location from one storm event to another.

The literature contains little information regarding typical size distributions of solids in stormwater runoff. However, one report published by California State University Sacramento (2002) reported size distributions recorded over a two-year span for highway runoff in the Lake Tahoe basin. The runoff analyzed upstream of any treatment system was reported to have the grain size distribution shown in Table 1 and Figure 1 (Note: Mass finer should decrease with decreasing grain size thus there appears to be a mistake in the values reported for grain sizes of 0.0328 and 0.0196 mm).

Ghani *et al.* (2000) also report grain size distributions of sediment in urban runoff for five cities in Malaysia with average d_{50} values (mm) of 0.6, 0.9, 0.8, 0.6, and 0.7. These values are similar to the d_{50} observed in the Lake Tahoe basin which, by interpolating values in Table 1, can be estimated to be 0.67 mm.

Grain Size (mm)	Mass Finer (%)	Grain Size (mm)	Mass Finer (%)
12.7	97.70	0.15	10.22
9.525	97.33	0.075	5.16
4.75	95.49	0.0716	0.80
2.36	91.25	0.051	0.73
2	84.12	0.0328	1.23
1.18	74.23	0.0196	1.06
0.85	56.84	0.0141	0.53
0.6	47.58	0.0102	0.45
0.425	30.78	0.0055	0.33
0.3	21.24	0.0024	0.20

Table 1. Grain size distribution of highway stormwater runoff in Lake Tahoe Basin.

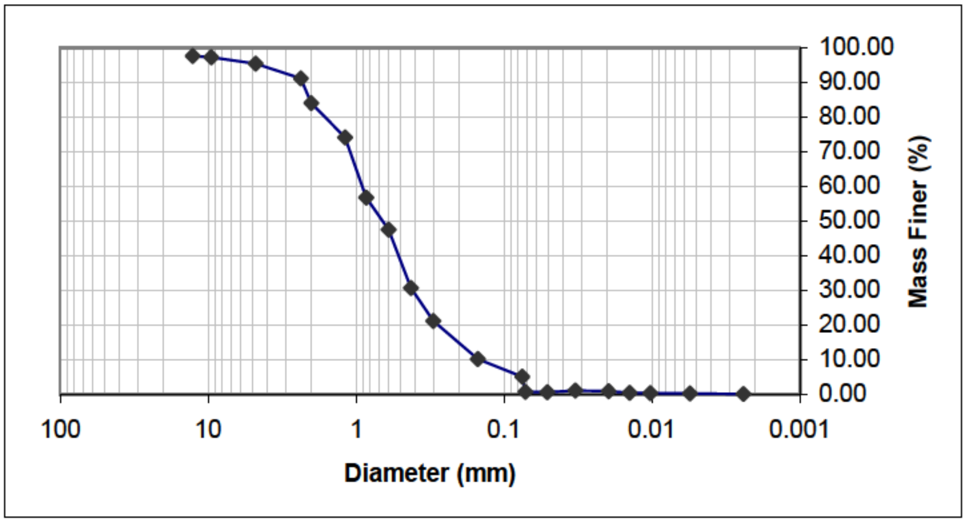

Figure 1. Grain size distribution of highway stormwater runoff in Lake Tahoe basin.

Removal of TSS and phosphorus from water may be achieved by a handful of different mechanisms. Much of the particulate or solid phosphorus can be removed via settling or mechanical filtration such as that which occurs in sand filters and when stormwater flows through adequately spaced and selected vegetation. As with particulate phosphorus, TSS levels may be reduced by settling and/or filtration.

To remove dissolved phosphorus from stormwater, the phosphorus must be converted, by means of a chemical reaction or adsorption, to a solid phase and removed as particulate (Jenkins *et al.*, 1971). In wastewater treatment applications, where ambient conditions can be more readily controlled, bacteria have been employed to convert dissolved phosphorus to the particulate phase. While the use of bacteria in stormwater treatment may be difficult, the use of wetland plants has rapidly become a commonly used process to remove both particulate and dissolved phosphorus. The plants filter TSS and particulate phosphorus out of the water while their roots absorb dissolved phosphorus. Both forms of phosphorus eventually end up in the sediments or plant matter. Once the plants have reached their capacity with regards to phosphorus, the wetland needs to be rehabilitated (typically dredged) in order to prevent the system from becoming a phosphorus source.

In an attempt to keep costs low, current SMPs typically do not include the construction of a treatment facility or a mechanical treatment process such as is commonly found in wastewater treatment plants. For example, some of today's most common SMPs include dry detention basins, wet/retention basins, constructed wetlands, infiltration practices, sand filters, grassed/vegetative swales, and filter strips, all of which will be defined and discussed below. Alternative options for low-cost solutions to pollutant removal may involve slight alterations to these common techniques to improve water quality treatment without significantly increasing construction or maintenance costs. For example, additional media such as limestone or steel wool has been added to sand filters to enhance dissolved phosphorus removal by precipitation and/or adsorption.

A report by Schueler *et al*. (1992) which summarizes studies that have determined removal efficiencies for several stormwater management practices and pollutants of concern is included in Appendix A. This collection illustrates the wide variability in pollutant removal effectiveness typically observed with SMPs.

The USEPA (1999) reported phosphorus removal efficiencies for several stormwater management practices as shown in Table 2. Also included are the minima and maxima data related to each median value, illustrating the range with which phosphorus removal efficiencies have been reported. In fact, every median reported came from a data set that included negative removal efficiencies indicative of phosphorus contributions to the effluent. Some of the most common SMPs, including those of Table 2, are explained in more detail below.

TYPE	Typical Phosphorus Removal (%)[1]	Median Removal Efficiency (%)			No. of Observations (respectively)
		Total	Dissolved	Ortho-	
Dry Detention Basin	15 - 45				
Wet/Retention Basins	30 - 65	46[3]	34[3]		44, 20
Constructed Wetlands	15 - 45	46[2]	23[2]	28[2]	37, 12, 7
Infiltration Basins	50 - 80	65[3]			5
Infiltration Trenches/Dry Wells	15 - 45				
Porous Pavements	30 - 65				
Grassed Swales	15 - 45				
Vegetated Filter Strips	50 - 80	15[3]	11[3]		18, 8
Surface Sand Filters	50 - 80	45[3]	-31[3]		15, 2
Other Media Filters	< 30				

Table 2. Expected phosphorus removal.

Sources: [1]modified from USEPA (1993), [2]Strecker (1992), [3]Brown and Schueler (1997)

To aid in evaluating the efficiency of stormwater management practices, the American Society of Civil Engineers (ASCE) and the USEPA have developed a website, www.bmpdatabase.org, which contains data regarding SMPs throughout the country. A team of stormwater experts have evaluated over 800 bibliographic sources and posted credible information from full and pilot scale and monitoring studies regarding the efficiency of scores of SMPs. They continue to review submissions and recent studies for incorporation into the database to provide the most accurate, relevant, and current information.

To better understand the cost-effectiveness of today's SMPs and to enable planners and engineers to make wise choices with limited resources, these SMPs must be reviewed for both their cost and contaminant removal potential and then compared amongst each other. While the final objective of this report is to provide such a comparison, a review and discussion of some common SMPs is presented below.

Dry Detention Basins

Definition: "Detention systems capture a volume of runoff and temporarily retain that volume for subsequent release. Detention systems do not retain a significant permanent pool of water between rainfall events." (USEPA, 1999a)

The primary function of dry detention basins is to reduce the risk of flooding by attenuating the peak storm flow rate by temporarily storing the runoff and releasing it through outlet structures. Compared to other SMPs, dry detention basins typically provide less water quality treatment. While properly designed detention basins can remove large solid particles via settling they often do not detain runoff long enough to allow finer particles to be removed. As the detention time of the basin is increased, however, the amount of solids removed will also increase. Also, dry detention basins may require frequent cleaning to reduce re-suspension during subsequent rainfall events (USEPA, 1999a). Of the phosphorus removed by a dry detention pond, most occurs by means of gravity settling of particulate phosphorus in the pond. Thus dry ponds usually remove little, if any, dissolved phosphorus.

Wet/Retention Basins

Definition: "Retention systems capture a volume of runoff and retain that volume until it is displaced in part or in total by the next runoff event. Retention systems therefore maintain a significant permanent pool volume of water between runoff events." (USEPA, 1999a)

Also termed wet ponds in some contexts, these basins are similar to dry detention ponds except the outlet structure is set at a higher elevation to create a permanent pool within the pond. Retention basins utilize gravity settling as the major removal mechanism but nutrient and organic removal can be achieved through aquatic vegetation and microorganism uptake. Figure 2 below shows a cross section of a retention pond illustrating this type of outlet structure.

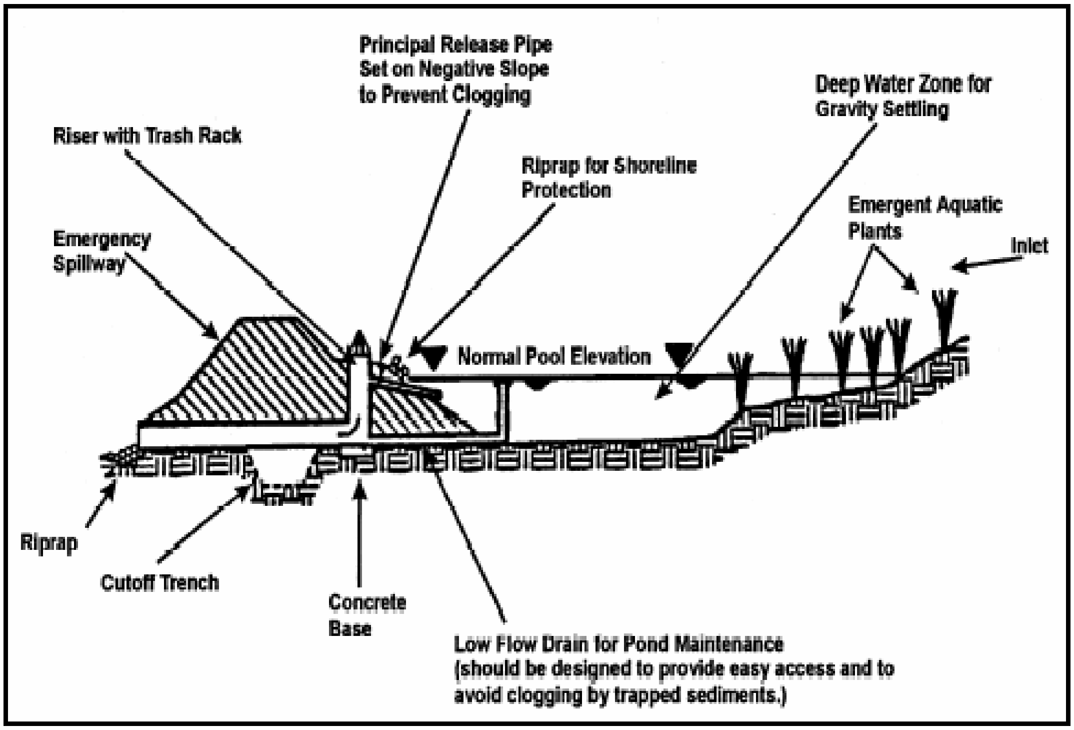

Figure 2. Retention basin cross section.

Source: Barr Engineering Company, 2001.

Limitations of these systems are typically related to retention time. During high flows, or freezing weather (when the permanent pool is frozen or covered with ice) influent runoff can short-circuit through the retention system and reduce the effectiveness of the sedimentation mechanism. Pond characteristics can also affect the removal efficiency. Changes in pH or hardness can alter the solubility of many contaminants and thus release them to the effluent (USEPA, 1999a). Another possible limitation of retention systems is high temperature effluent.

The water in the pond may absorb enough solar energy to significantly increase the temperature of the effluent which may adversely impact fish and other aquatic species in the receiving waters.

Constructed Wetlands

Definition: "Constructed wetland systems are similar to retention and detention systems, except that a major portion of the SMP water surface area (in pond systems) or bottom (in meadow-type systems) contains wetland vegetation. This group also includes wetland channels." (USEPA, 1999a)

Constructed wetlands are similar to dry basins in that they release inflow much more slowly as effluent. They also resemble wet/retention basins in that, although they are shallower, they typically hold a permanent pool of water to maintain wetland vegetation. Whereas dry detention basins are typically designed to release the entire stormwater inflow within 24 to 48 hours, constructed wetlands can take several days or more to release runoff events. Figure 3 shows one potential design of a constructed wetland system, although several configurations and systems are identified as constructed wetlands.

Constructed wetlands allow for more removal mechanisms than detention basins and longer contact times than retention basins; therefore they are capable of removing more pollutants such as nutrients and organics. Unlike dry detention basins, constructed wetlands, if designed properly, do not allow for re-suspension of particles and contaminants. However, a major drawback of constructed wetlands is the large space they require. Constructed wetlands typically require large areas to allow for adequate storage volumes and long flow paths. As a result wetlands are often impractical in urban and suburban areas where land costs are high. Another limitation of constructed wetlands (perhaps retention systems also) is nuisance fowl and insects as wetlands can provide breeding grounds for mosquitoes and other pests.

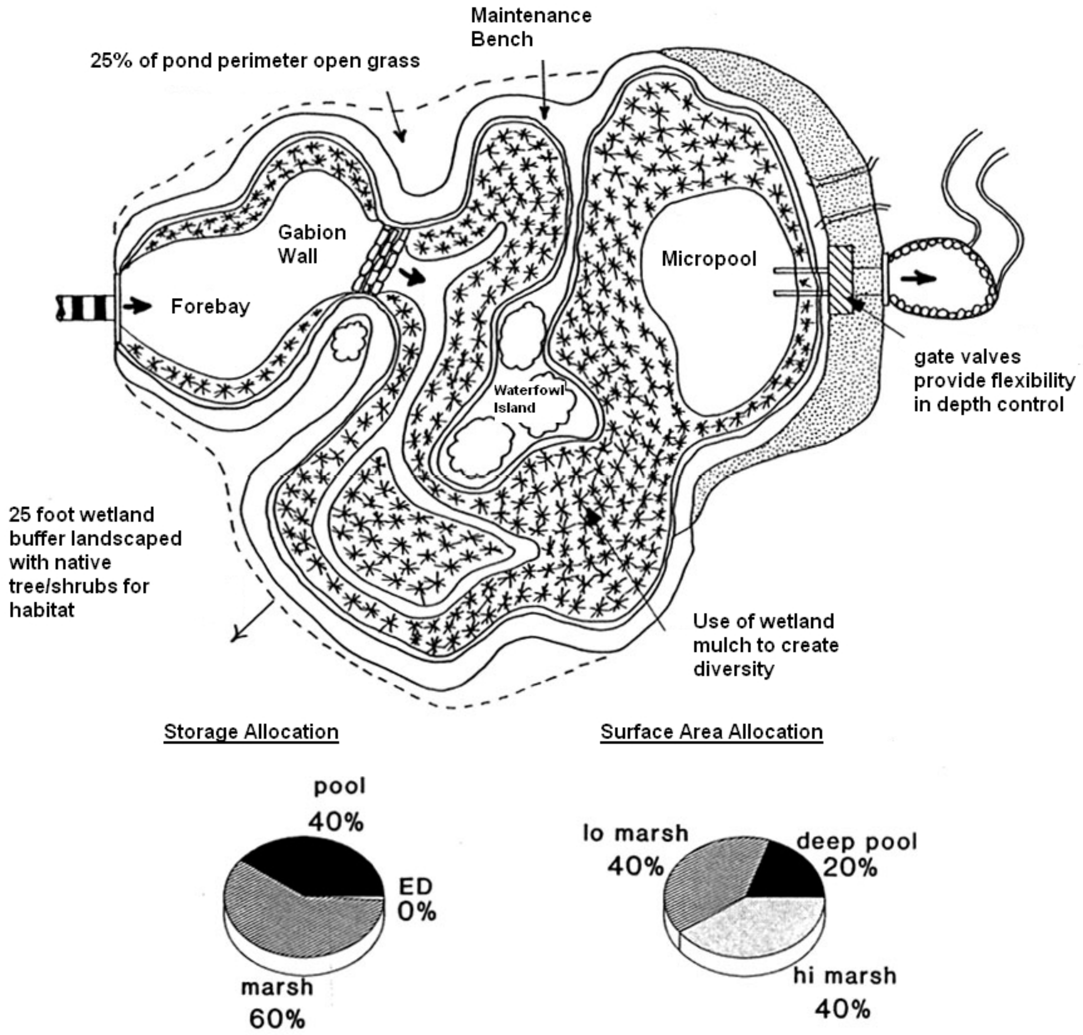

Figure 3. One example of a constructed wetland system.

Source: Barr Engineering Company, 2001.

As with any SMP, constructed wetlands require regular maintenance to remain effective. Faulkner and Richardson (1991) attributed a significant reduction in nutrient removal to the wetland vegetation reaching maximum density. Thus, wetlands plants may have to be harvested to remove overabundant vegetation. Furthermore, overabundant and decaying vegetation can deposit large amounts of soluble and particulate phosphorus into the wetlands system; typically more than the living vegetation can uptake. This can result in an addition of phosphorus to the system. However it is questionable if harvesting plants will adequately remove phosphorus because in studies where vegetation has been harvested in an attempt to remove phosphorus, only minimal amounts of phosphorus have been recovered (Kadlec and Knight, 1996). These factors may make it difficult for constructed wetlands to be a long-term cost-effective quality control technique.

As with other SMPs, removal efficiencies of TSS and P for constructed wetlands vary widely among monitoring studies. This may be partly attributed to the fact that constructed wetlands can lose their capacity to remove phosphorus over time (Oberts, 1999). Even when phosphorus removal occurs, wetlands usually remove a significantly higher fraction of TSS than phosphorus.

Infiltration Practices

Definition: “Infiltration systems capture a volume of runoff and infiltrate it into the ground” (USEPA, 1999a). Any technique that does not discharge effluent to surface waters, or reduces total discharge, can be categorized as an infiltration practice. Infiltration practices encompass a number of techniques utilized for the treatment of stormwater runoff. Most infiltration practices require some form of pretreatment along with frequent maintenance to prevent blockage and ensure proper operation of the system.

The removal performance of infiltration practices has not been thoroughly reported. The difficulty in determining the quality of the effluent is most likely the chief reason for this lack of information. The data regarding infiltration practices that is available varies drastically due to many factors such as varying soil conditions, influent water quality, depth to water table, degree of pretreatment, maintenance protocols, etc. In areas with highly permeable soil, poor quality effluent may not receive adequate contact time and may be released to aquifers with little or no treatment (USEPA 1999a). It is also very difficult to monitor the effluent of infiltration practices and confidently report that the findings are solely attributed to the infiltration system itself. Four common infiltration practices are discussed below.

Infiltration Basins

Infiltration basins are similar to detention or retention basins in design and appearance, but do not use an outlet structure to convey effluent, except when the runoff volume is too large and cannot be stored in the basin. These basins release treated water directly to the groundwater after filtration through the basin media which may be comprised of the existing soil and/or a specified filtration media introduced during construction. As mentioned previously, an overflow outlet to a receiving water body is usually installed to discharge the excess water volume of large storms.

Infiltration Trenches

Infiltration trenches can be thought of as constructed channels filled with filtration media or soil which allows for the infiltration of stormwater. These trenches are often placed around the perimeter of parking lots or other structures to treat the runoff generated by the site. With sufficient sizing and properly designed flow regulators (typically check dams), infiltration trenches can infiltrate a large portion of the runoff. Figure 4 shows an example of a typical infiltration trench design.

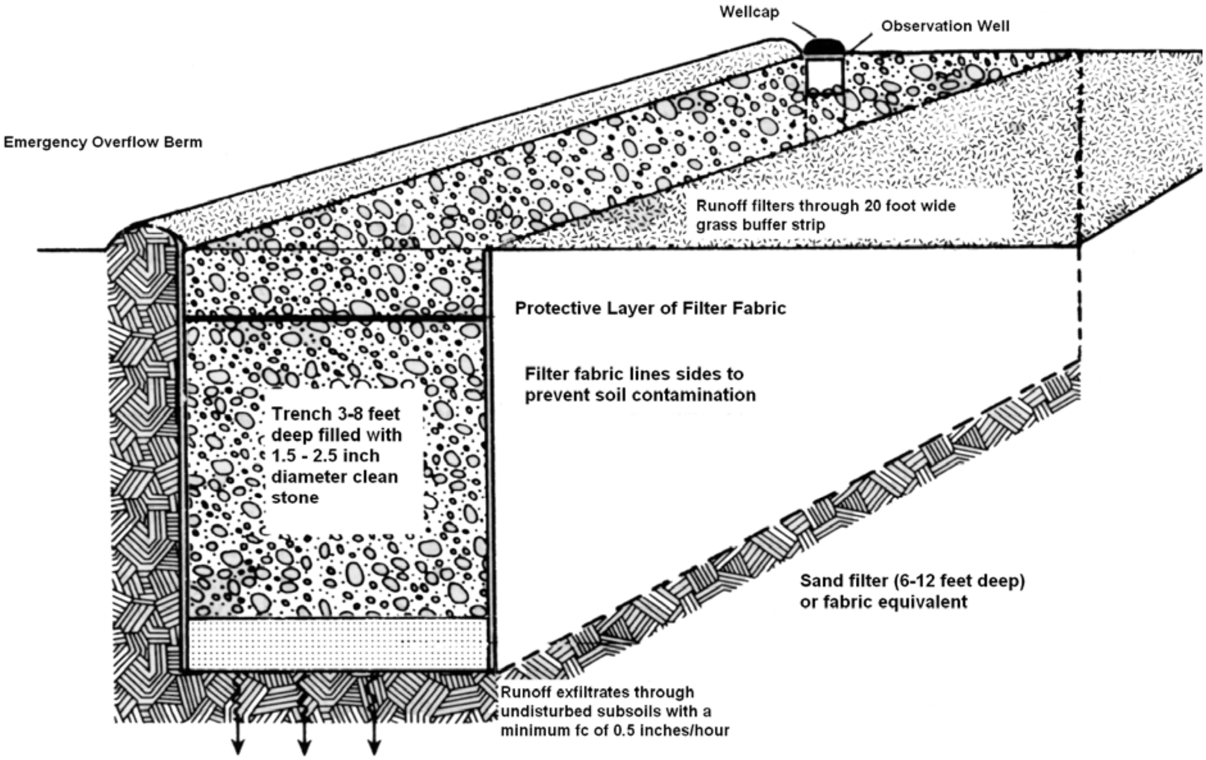

Figure 4. Infiltration trench design.

Source: Barr Engineering Company, 2001.

Bioretention

While not specifically defined by the USEPA, bioretention systems are essentially landscaped depressions to which stormwater runoff is diverted and stored. Once in the depression, the landscaped trees, shrubs, and other vegetation help to remove the water through uptake, while the runoff infiltrates into the soil below. The underlying soil may consist of the original soil or it may be non-native soil such as sand that is installed during construction. Also, depending on the permeability of the underlying soil, a bioretention system may include a perforated underdrain which collects and removes infiltrated water.

Bioretention systems are rapidly gaining in popularity because it is assumed they incorporate the best of vegetative systems and filtration systems. However, their impact on water quality is neither well known nor documented.

Porous Pavements

Definition: "Porous pavement systems consist of permeable pavements or other stabilized surfaces that allow stormwater runoff to infiltrate through the surface and into the groundwater." (USEPA, 1999a)

Porous pavement comes in many forms, some of which are commercially available. Unlike typical asphalt or concrete pavements, porous pavements allow runoff to seep through the pavement surface which reduces the amount of runoff. Porous pavements are categorized as an infiltration practice because they allow runoff to infiltrate into the underlying soil.

Limitations of porous pavements are similar to other infiltration practices and usually involve maintenance and clogging issues. Porous pavements typically contain small voids (or seams between bricks) that can become clogged with sediments. Frequent surface vacuuming or flushing is usually required to keep porous pavements free of sediments and other debris, allowing prompt infiltration of surface runoff.

Water quality treatment of runoff by porous pavements is similar to that of other infiltration practices. The porous pavement itself provides little actual removal while the infiltration of the runoff to receiving groundwater can remove significant amounts of contaminants.

Sand Filtration

Definition: Sand filtration systems utilize granular media to filter stormwater runoff that is collected and discharged as effluent to other treatment systems or directly to receiving waters. Those called "Austin" sand filters appear much like a dry detention basin but include built-in sand filled areas that filter the water and release it to an underdrain. The "Delaware" sand filters are usually smaller, low retention filters that can be placed underground in concrete chambers and are typically designed to capture and treat only the first portion (often called the "first flush") of most runoff events.

Herrera Environmental Consultants (1995) performed a study which showed that sand filters provide little (*i.e.* 20 - 50 % total, 5 - 30 % soluble) capacity for phosphorus removal compared to other SMPs. Anderson *et al*. (1985) monitored several water-quality parameters of more than a dozen intermittent sand filters for the USEPA. Their results also concur that a pure sand-filter media provides "only limited removal of phosphorus" (Anderson, 1985).

Harper and Herr (1993) performed pilot-scale and full-scale monitoring studies in Florida for the removal of several water quality contaminants. It was estimated that typical sand filters remove approximately 40 to 50 percent particulate and total phosphorus, but at most only five percent soluble phosphorus. Another sand filter utilizing a silica sand media exhibited better results for soluble and total phosphorus (35 and 55 percent, respectively) but also contributed particulate phosphorus to the effluent. Harper and Herr acknowledged that the silica sand was considerably coarser than the typical sand media used in their other experiments. Harper and Herr (1993) also conducted experiments comparing sod coverings placed on top of sand filters. Four types of sod were tested in a fashion similar to their previous study. It was determined that all but one sod covering contributed dissolved phosphorus to the effluent, and removal rates for particulate or total phosphorus were at most 54 percent.

The full scale monitoring performed by Harper and Herr (1993) encompassed many water quality and quantity characteristics of a basin that incorporated both infiltration and filtration practices in what the authors deemed a “Wet detention basin.” By performing a mass balance on the pond it was determined that the pond removed roughly 30 to 40 percent of the ortho-phosphorus, 80 percent of the particulate phosphorus, and 60 percent of the total phosphorus over the six month monitoring period. However, the configuration of the pond created a permanent pool of water which allowed for algae growth. Harper and Herr (1993) attribute the high removal rates of ortho-phosphorus to algae uptake by the biomass that developed within the pond and the particulate phosphorus removal to filtration processes.

Bell *et al.* (undated) conducted an assessment of Delaware (also referred to as intermittent) sand filters for their removal efficiencies of several pollutants found in urban stormwater runoff. The study was based on the monitoring of an existing sand filter constructed in Northern Virginia (pg. 5-1) over the course of 20 storm events during the summer of 1994. Among many other pollutants, Bell *et al.* reported removal rates of up to 90 percent for phosphorus (pg. 5-20) and suggested that their results “may not reflect the true potential of intermittent sand filter BMPs.” Even though average removals of 60 to 70 percent were reported, an analysis of the filter media revealed constituents of iron (3000 mg/kg), calcium (4-6 mg/kg), and aluminum (2900 mg/kg). Based on evidence provided by Baker *et al.* (1997) and Anderson *et al.* (1985), it can be postulated that these “involuntary” additives affected the removal efficiencies of the sand filters assessed by Bell *et al.* (undated).

Other additives such as peat or compost have been studied for their effectiveness at removing contaminants from stormwater runoff. Farnham and Noonan (1988) conducted a study of peat-sand combination filter efficiencies and reported a direct relationship between phosphorus removal efficiency as percent removal and input phosphorus concentration. Galli (1990) also suggested the use of a peat-sand filter for urbanized runoff treatment and predicted 70 percent removal of total phosphorus for peat species that contain minimal, if any, phosphorus content. The USEPA monitored a filter built to Galli's design specifications and reported instances of both phosphorus removal and phosphorus addition through leaching of the media into the water (USEPA, 1999a, pg. 5-80, 5-81). Other sources (Koerlsman *et al*., 1993) have also reported peat as a source of phosphorus when used as filter media. Stewart (1992) reported that a leaf compost filter can also leach phosphorus into stormwater effluent (Section 3, Table 12).

Vegetated Systems

Definition: "Vegetated systems such as grassed swales and filter strips are designed to convey and treat either shallow flow (swales) or sheet flow (filter strips) runoff." (USEPA, 1999a)

Vegetated systems are a special application of infiltration practices that utilize vegetated cover for two purposes. Vegetated cover on sloped applications slow the overland flow to allow greater opportunity for infiltration into the soil while also providing an opportunity for nutrient uptake through the root system. Vegetated systems suffer the same monitoring difficulties as other infiltration practices, and can be more difficult to maintain. As with infiltration trenches and basins, vegetated systems can become clogged with particles and debris in the absence of proper pretreatment and maintenance. In some cases the sediment deposits can begin to choke out the vegetated cover and create an erodible surface capable of contributing sediment and other pollutants directly downstream.

Commercial Products

Commercially available products include, but are not limited to, DrainPac™, HydroKleen™, StormTreat^{TM} System, BaySaver™, Stormceptor®, Vortechs ™, Downstream Defender®, Continuous Deflective Separation (CDS®), and StormFilter™. Other commercially available products are available and new products will almost certainly be introduced in the future. Brueske (2000) performed a review of several commercial products, however an unbiased review of the performance of these products can be difficult to obtain and reported removal rates must be used with caution. The relatively small size of the commercial products (as compared to wet basins, wetlands, detention ponds, etc.) may result in their long-term effectiveness being much lower than reported. For example, one product with a reported TSS removal rate of over 80% was field tested and found to remove only about one-third of the sediment load and 19 percent of total phosphorus (Waschbusch, 1999).

Review Summary

The ability of SMPs to remove TSS and phosphorus effectively is dependant on many factors and can occur by various mechanisms. Many researchers have studied SMPs for their capability to remove TSS and phosphorus and some have investigated the mechanisms by which removal occurs. Designers, planners, and other decision makers have little guidance that incorporates this information in combination with SMP costs to aid them in the selection of a SMP. Comparisons of the cost-effectiveness of SMPs are, at best, rare and yet decision makers are continually forced to spend limited resources on technologies whose costs and benefits are not well understood. A comparison of this nature would enable decision makers to better appropriate limited resources as they strive to meet federal regulations by improving the water quality of stormwater effluent.

This report helps fill a critical knowledge gap by quantitatively comparing the cost and effectiveness of several of the most common SMPs for which reliable data was available. More direct comparisons, however, are needed, including comparisons with and between commercial products.

Cost Estimation

Based on published cost data of actual SMPs a method, which is described below, was developed that will enable designers and planners to make estimates of the Total Present Cost (TPC) of various SMPs if the size of the SMP is known. In this report, the TPC is defined as the present worth of the total construction cost of the project plus the present worth of 20 years of annual operating and maintenance (O&M) costs. The values reported do not include costs of pretreatment units (which may be required), design or engineering fees, permit fees, land costs, or contingencies, etc.

Water Quality Volume

The costs of SMP projects are usually reported along with the corresponding watershed size (usually in acres or square feet) and/or the water quality volume (WQV) for which the SMP was designed. The water quality volume is often defined as the volume (typically in acre-feet or cubic feet) of runoff that the SMP is designed to store and treat.

Claytor and Schueler (1996) calculate the WQV (ft^3) for a particular precipitation amount as:

$$\mathrm{WQV} = \left(\frac{43560}{12}\right) * \mathrm{P} * \mathrm{R_V} * \mathrm{A} \tag{1}$$

where: P = Precipitation depth (inches)

R_V = Ratio of runoff to rainfall in the watershed

A = Watershed area (acres), and the constants are conversion factors.

The ratio of runoff to rainfall, R_V, has the most uncertainty of the parameters in Equation 1. For this analysis, a relatively simple relationship was used (Claytor and Schueler, 1996; Young et al., 1996)

$$\mathrm{R_V} = 0.05 + 0.009 * (\mathrm{I}) \tag{2}$$

where I is the percent (0-100) of the watershed that is impervious. Equation 2 indicates that, for a 100% impervious watershed, 95% of the rainfall becomes runoff.

Total Construction Costs

Values of total construction costs of SMPs throughout the United States were collected from published literature. Although data was collected on many SMP technologies, sufficient data to perform a cost analysis could be found for only dry detention basins, wet/retention basins, constructed wetlands, infiltration trenches, bioinfiltration filters, sand filters, and swales. All data were adjusted to reflect costs in Minnesota by means of ‘Regional Cost Adjustment Factors’ as reported by the United States Environmental Protection Agency (USEPA, 1999a) and were also adjusted to year 2005 dollars using an annual inflation rate of 3 percent. A value of 3 percent was chosen after an analysis of building cost indexes for the past 11 years (Turner Construction, 2004) revealed that the average annual inflation was 3.26 percent with a range from 0.3 to 5.4 percent.

The cost data which was collected was usually reported in conjunction with the watershed area and/or the water quality volume (WQV) for which the particular SMP was designed. When the cost data was converted to unit construction costs, defined as the total construction cost per acre of watershed or per cubic foot of WQV, the data, in all cases except for bioinfiltration filters, exhibited an Economy of Scale. In other words, when the unit construction cost was plotted versus the size (*i.e.* watershed area or WQV), the unit cost tended to decrease as the size increased. As mentioned, the only exception to this trend was bioinfiltration filters which exhibited a slight increase in unit cost with increasing size.

When comparing unit-cost data based on watershed area and WQV, the data based on WQV was, in most cases, observed to have less scatter as quantified by the standard error of the y-estimate. Thus, in order to provide for as much consistency as possible while minimizing scatter overall, WQV-based unit construction costs were selected for use over watershed area based unit construction costs. However, there was insufficient data to allow for a WQV-based approach when considering grassed/vegetative swales. Furthermore, basing a cost analysis of a swale, which is usually designed for a peak flow rate and could have a wide variety of lengths, on watershed area or WQV does not make intuitive sense. Instead, projected cost estimates per linear foot of swale as a function of geometry were collected and analyzed. Using these data, the cost per linear foot of a grassed/vegetative swale was found to be a function of the top width of the swale. Thus, a second method, used only to estimate the construction costs of swales, was developed and is based on construction cost per linear foot as a function of swale top width.

Figures 5 through 11 below show the unit construction cost data analyzed in graphical form. Also shown is the dashed, best-fit line through the data and the 67% confidence interval as shown by solid lines on either side of the best-fit line. The 67% confidence interval shows the bounds that will, on average, contain 67% of the data. In other words, one-third of the data could fall outside of the 67% confidence interval. If there is sufficient data (~20) and the distribution is, in this case, truly log-normal, then one-third of the data will fall outside of the 67% confidence interval. The data originating from Brown and Schueler (1997) were read graphically whereas the values from SWRPC (1991), Caltrans (2004), and ASCE (2004) were given in tabular form. The data from Caltrans (2004) was collected by means of a survey distributed by Caltrans to other agencies throughout the country. It should be noted that the total construction costs of SMPs installed by Caltrans were also available but these values were omitted from this

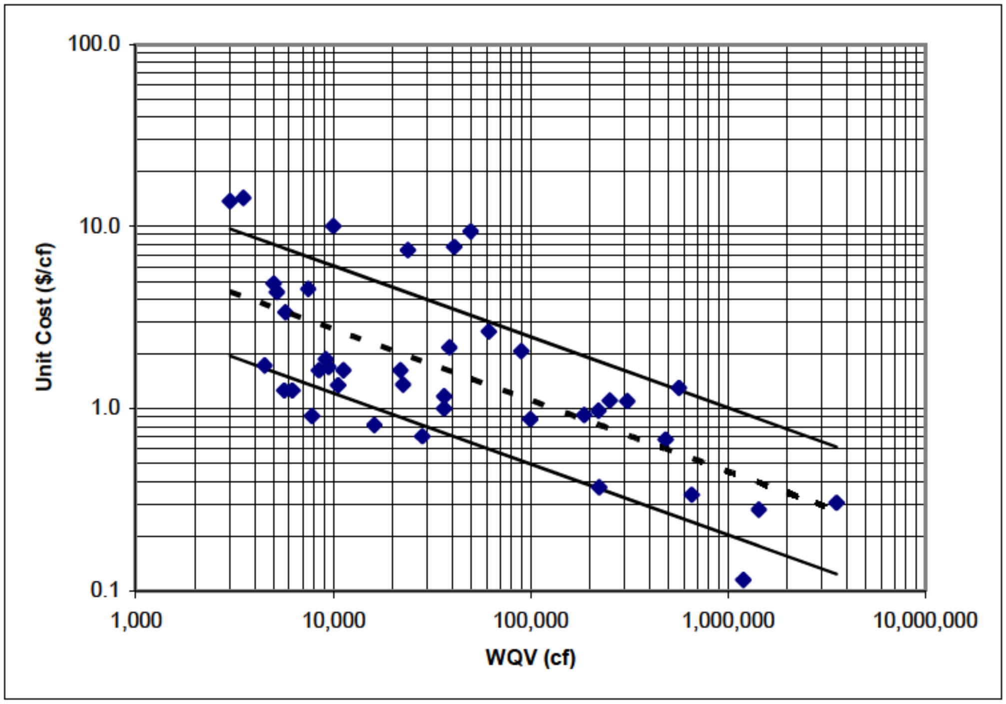

Figure 5. Unit construction costs of dry detention basins.
(Data from Brown and Schueler, 1997; ASCE, 2004; Caltrans, 2004)

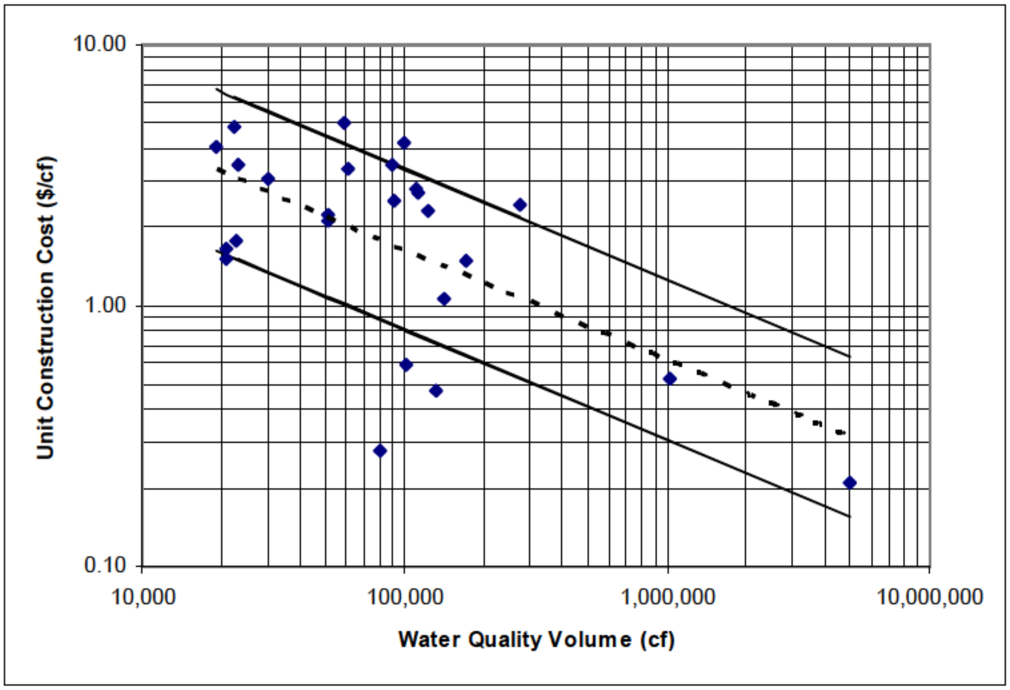

Figure 6. Unit construction costs of wet basins.

(Data from Brown and Schueler, 1997; Caltrans, 2004)

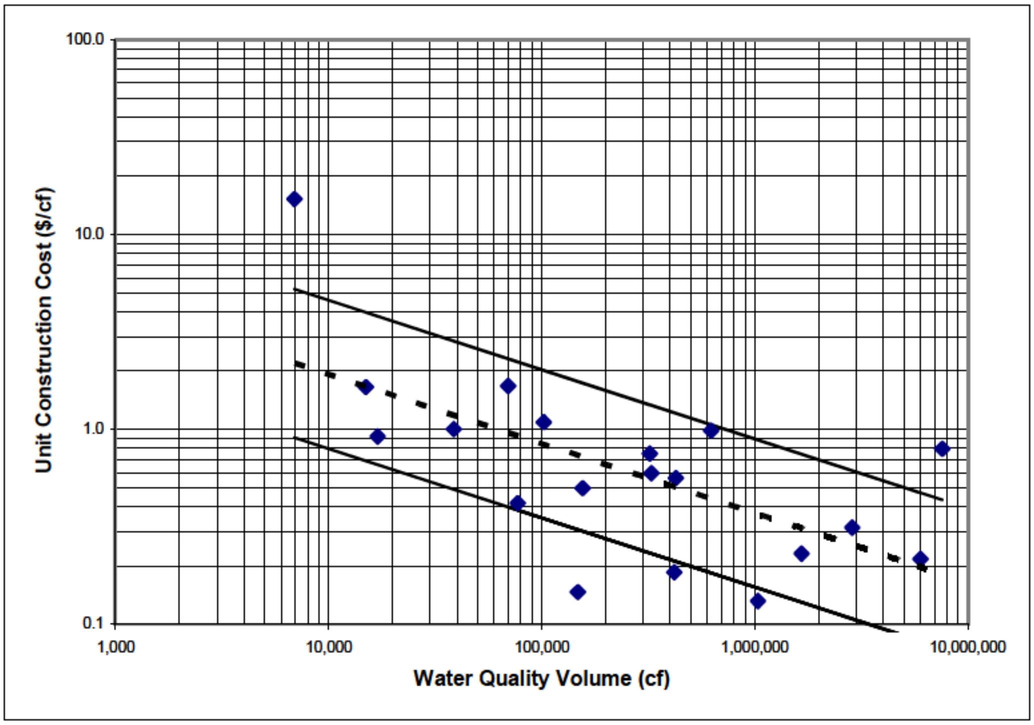

Figure 7. Unit construction costs of constructed wetlands.

(Data from Brown and Schueler, 1997, Caltrans, 2004; ASCE, 2004)

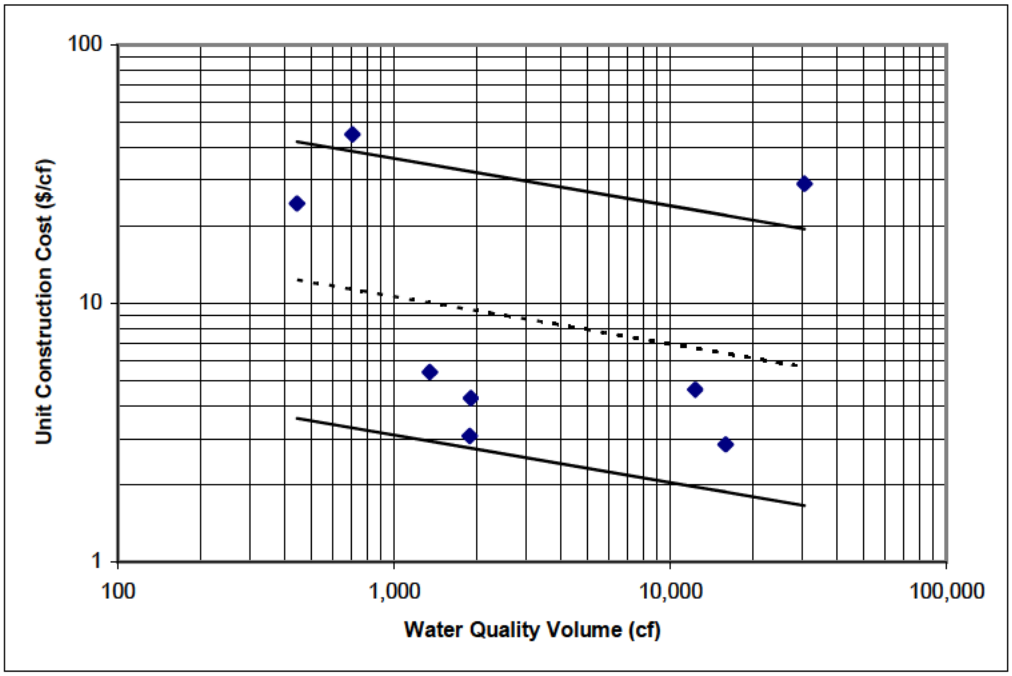

Figure 8. Unit construction costs of infiltration trenches.

(Data from Caltrans, 2004)

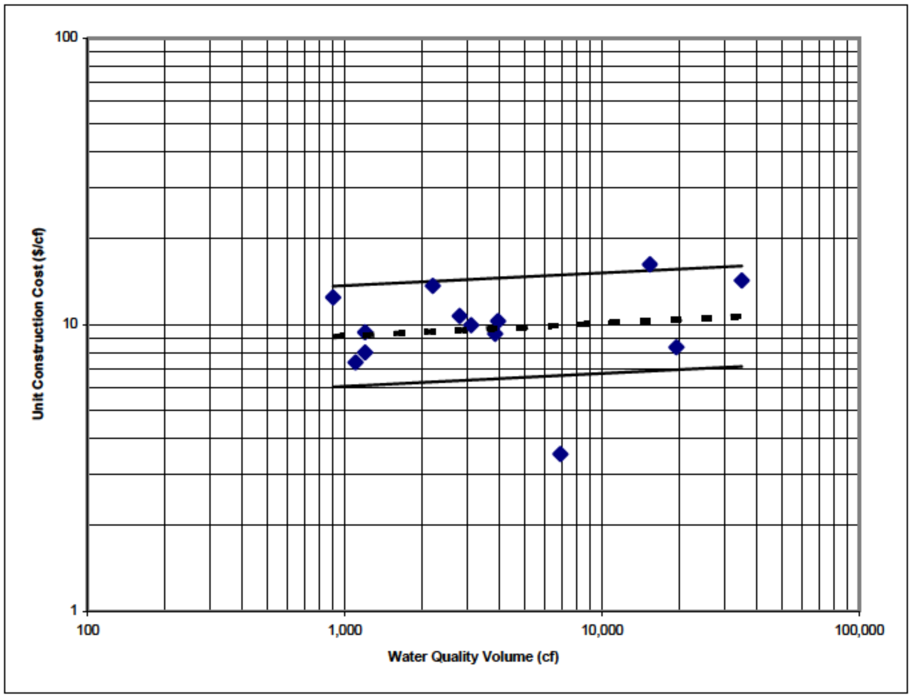

Figure 9. Unit construction costs of bioinfiltration filters.

(Data from Brown and Schueler, 1997; Caltrans, 2004)

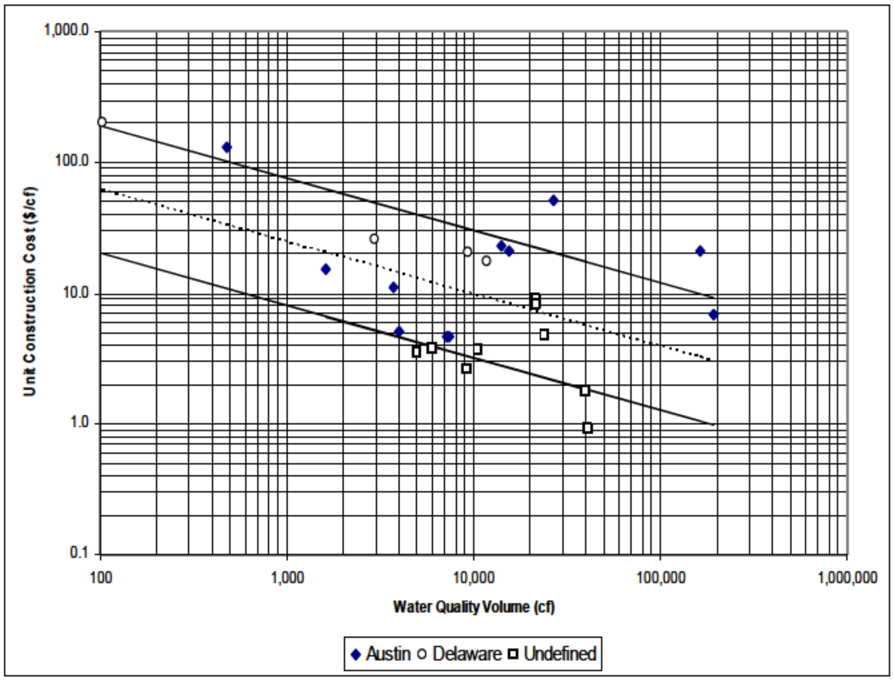

Figure 10. Unit construction costs of sand filters.

(Data from Brown and Schueler, 1997; Caltrans, 2004)

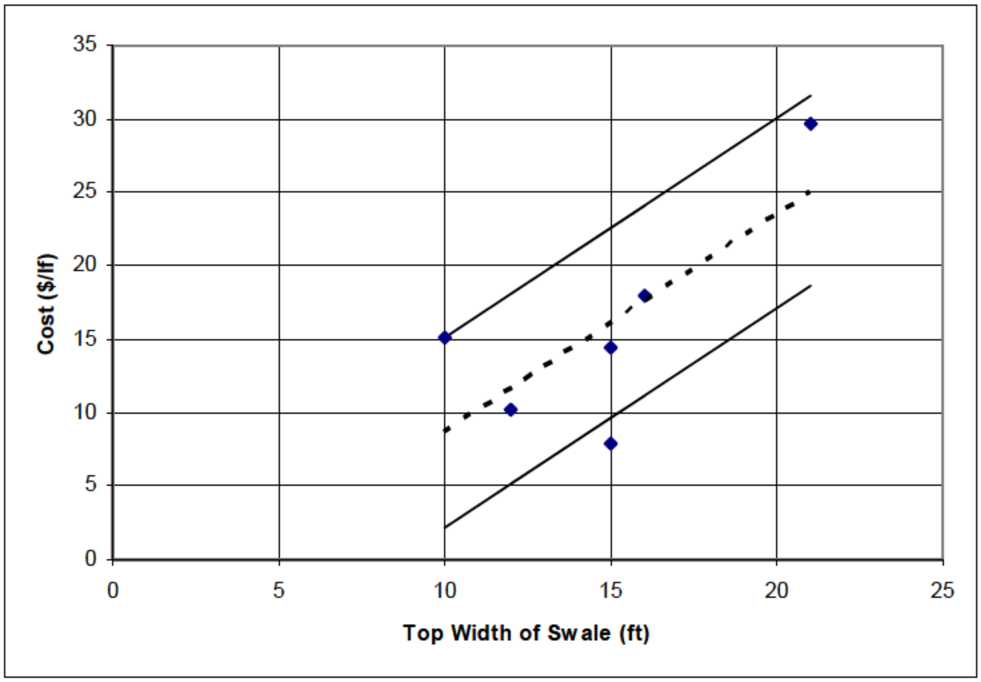

Figure 11. Unit construction costs of grassed/vegetative swales.

(Data from SWRPC, 1991)

analysis because their costs were typically about ten times higher than similarly sized projects constructed by other agencies. Caltrans attributed these high costs to the fact that their projects were retrofits and were not installed as part of larger construction projects.

Of the data collected for sand filters, some contained information on the type of sand filter (*e.g*. Austin or Delaware) while other data included no such description. Interestingly, when analyzing the sand-filter data for unit costs, there was essentially the same amount of scatter when the data of each sand-filter type was analyzed alone as there was when all sand-filter data was combined and analyzed together. This suggests that sand-filter unit-construction costs are independent of the type of filter and, as a result, cost estimates developed herein do not differentiate between sand-filter types. Figure 10 does differentiate between the Austin, Delaware, and undefined data by the data marker but, since no trend was observed for individual filter types, the best-fit line is drawn through the combined data.

The uncertainty observed in the data for all SMPs is most likely due to several factors such as design parameters, regulation requirements, soil conditions, site specifics, etc. For example, variable design parameters that would affect the total construction cost include pond side slopes, depth and free board on ponds, total wet pond volume, outlet structures, the need for retaining walls, etc. Site specific variables include clearing and grubbing costs, fencing around the SMP, etc. Due to the wide number of undocumented variables that affect the data, this scatter would be extremely difficult, if not impossible, to minimize.

Later in this report the data shown in Figures 5 through 11 will be combined with annual O&M cost data to estimate the TPC of each SMP as a function of size. After a discussion of typical land-area requirements, the methods and data used to incorporate O&M costs into this analysis are described.

Land-Area Requirements

An important cost of any SMP is that of the land area on which the SMP will be located. For urban areas, in which land is typically at a premium, this cost can be relatively large. On the contrary, in more open, rural areas, land costs might be a very small percentage of the total project costs. Due to the extreme range of land costs and variability from site to site, no attempt was made to incorporate this cost into the Total Present Cost analysis. However, the land area requirements, and therefore the associated land costs, of each SMP technology can vary dramatically and would, in many scenarios, have a significant impact on the total cost of a project. For example, a sand filter placed underground, below a parking lot would, in effect, require no additional land area. However, a constructed wetland designed to treat the same volume of runoff as the underground sand filter would require significant additional land area that may preclude the use of wetlands. Given the variability of land costs and the variety of potential SMPs that could be used, the impact of land costs must be done on an individual, case-by-case basis. Table 3, which lists typical SMP land-area requirements for effective treatment, is presented to assist designers and planners in making such a comparison. Values reported in Table 3 by Claytor and Schueler (1996) are for the general category of SMP system and may include more than one specific type of SMP. For example, their pond category may include both wet and dry ponds. Table 4 lists wet pond areas required for control of particles that are 5 and 20 microns in size as reported by Pitt and Voorhees (1997). If the land costs in the locale of a particular project are known, these costs can be combined with the information presented in the tables to estimate a range of possible land area costs associated with each SMP under consideration. This information is intended to give only a possible range of land area costs. For more accurate land area cost estimates, a preliminary SMP design should be performed.

SMP System	SMP Area (% of Impervious Watershed) From USEPA, 1999.	SMP Area (% of Watershed) From Claytor and Schueler (1996) Except as noted.
Bioretention	5	--
Wetland	3 - 5	3 - 5
Wet/Retention Basin	2 - 3	--
Sand Filter	0 - 3	--
Dry Det Basin	--	0.5 - 2.0 (UDFCD, 1992)
Infiltration Trench	2 - 3	--
Filter Strips	100	--
Swales	10 - 20	--
Pond	--	2 - 3
Infiltration	--	2 - 3
Filter	--	2 - 7

Table 3. Reported SMP land area requirements for effective treatment.

Land Use	5 micron control	20 micron control
100% Paved	3.0	1.1
Freeways	2.8	1.0
Industrial	2.0	0.8
Commercial	1.7	0.6
Institutional	1.7	0.6
Residential	0.8	0.3
Open Space	0.6	0.2
Construction	1.5	0.5

Table 4. Typical land area requirements (% of total watershed) for wet ponds (i.e. basins).

(Pitt and Voorhees, 1997)

Operating and Maintenance Costs

Over the lifetime of a SMP, the operating and maintenance costs can be a significant expense that must be considered when selecting a treatment method. However, no data was found that documented actual O&M costs of existing SMPs. At best, available data consisted only of expected or predicted O&M costs of recently constructed SMP projects. Often times, general guidelines of estimated annual O&M costs were presented as a percentage of the total construction cost. For example, the USEPA (1999a) gives a summary of typical SMP annual O&M costs as shown in the middle column of Table 5. Also included in the right column of Table 5 is the range of the authors' collection of predicted O&M costs as a percent of the construction cost.

Ideally the estimate of TPC would be based on actual O&M costs of existing SMPs but, as mentioned above, estimated annual O&M costs were the only available data. When this data was evaluated to determine how the estimated O&M costs compared to those summarized by the USEPA, a trend was observed for all SMPs except infiltration trenches in which the annual O&M cost as a percentage of the construction cost decreased with increasing construction cost. The collected annual O&M cost data are shown as log-log plots in Figures 12 through 18. As with the construction cost data, the best-fit line through the data and the 67% confidence interval are shown.

SMP	Summary of Typical AOM Costs (% of Construction Cost) (USEPA, 1999A)	Collected Cost Data: Estimated Annual O&M Costs (% of Construction Costs)
Retention Basins and Constructed Wetlands	3%-6%	--
Detention Basins	<1%	1.8%-2.7%
Constructed Wetlands	2%	4%-14.1%
Infiltration Trench	5%-20%	5.1%-126%
Infiltration Basin	1%-3% 5%-10%	2.8%-4.9%
Sand Filters	11%-13%	0.9%-9.5%
Swales	5%-7%	4.0%-178%
Bioretention	5%-7%	0.7%-10.9%
Filter Strips	$320/Acre (maintained)	--
Wet Basins	Not Reported	1.9%-10.2%

Table 5. Typical annual O&M costs of SMPs.

In the following section the annual O&M costs will be combined with the unit construction costs to develop an estimate for the Total Present Cost of each SMP as a function of WQV or, in the case of swales, as a cost per linear foot as a function of swale top width.

Total Present Cost

If an estimate of the total construction cost of a SMP were desired, the data presented in Figures 5 through 10 could be used in a stand-alone manner simply by multiplying the unit construction cost ($/ft^3) by WQV (ft^3). The construction cost of swales could also be easily estimated by multiplying the unit cost ($/ft) by the swale length (ft). However, a more practical estimate is that of the total costs needed to not only construct but also to maintain and operate the SMP. Rather than provide one estimate for total construction cost and another estimate for annual O&M expenditures, the data presented in the previous two sections will be combined in

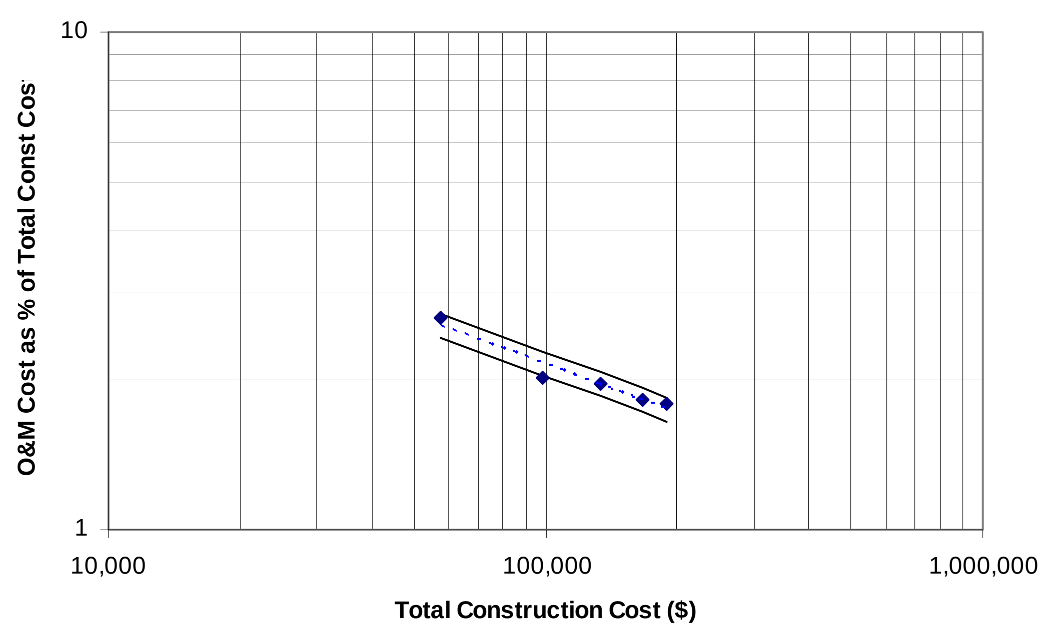

Figure 12. Annual O&M costs of dry detention basins.
(Data from Landphair, *et al*, 2000)

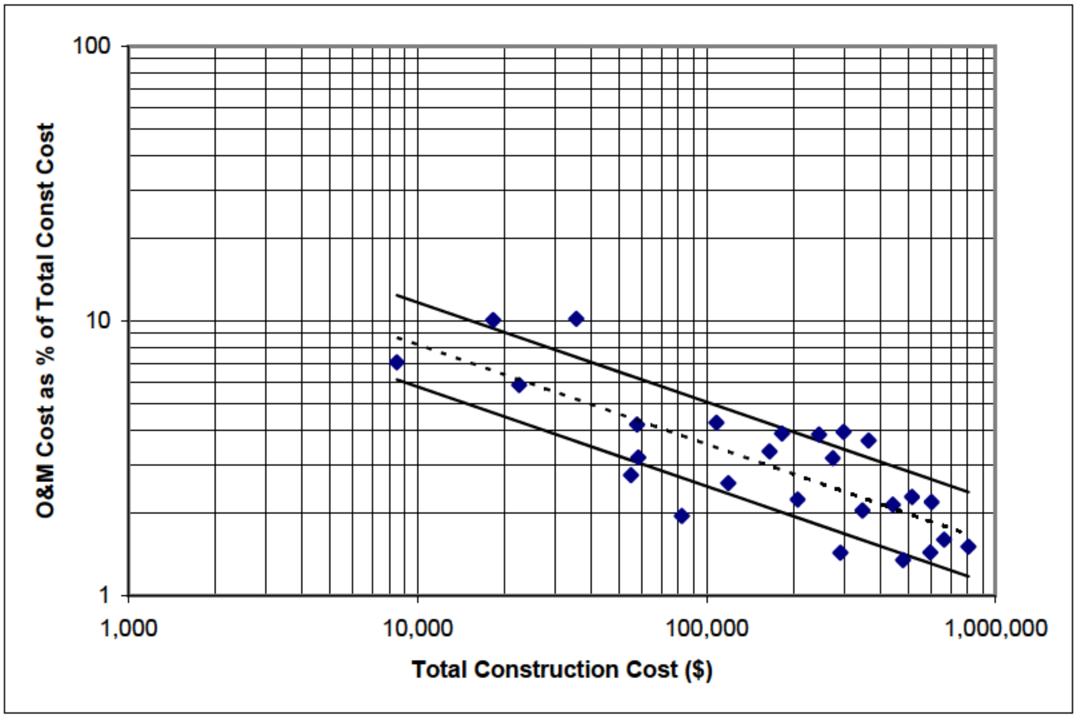

Figure 13. Annual O&M costs of wet basins.

(Data from SWRPC, 1991; Wossink and Hunt, 2003)

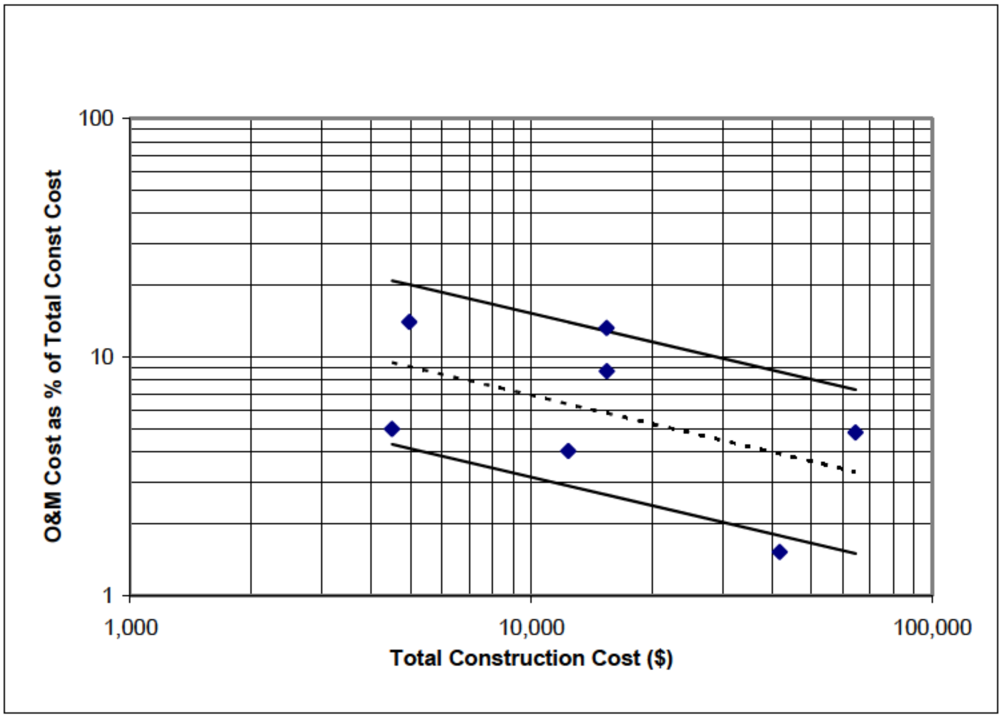

Figure 14. Annual O&M costs of constructed wetlands.

(Data from Wossink and Hunt, 2003)

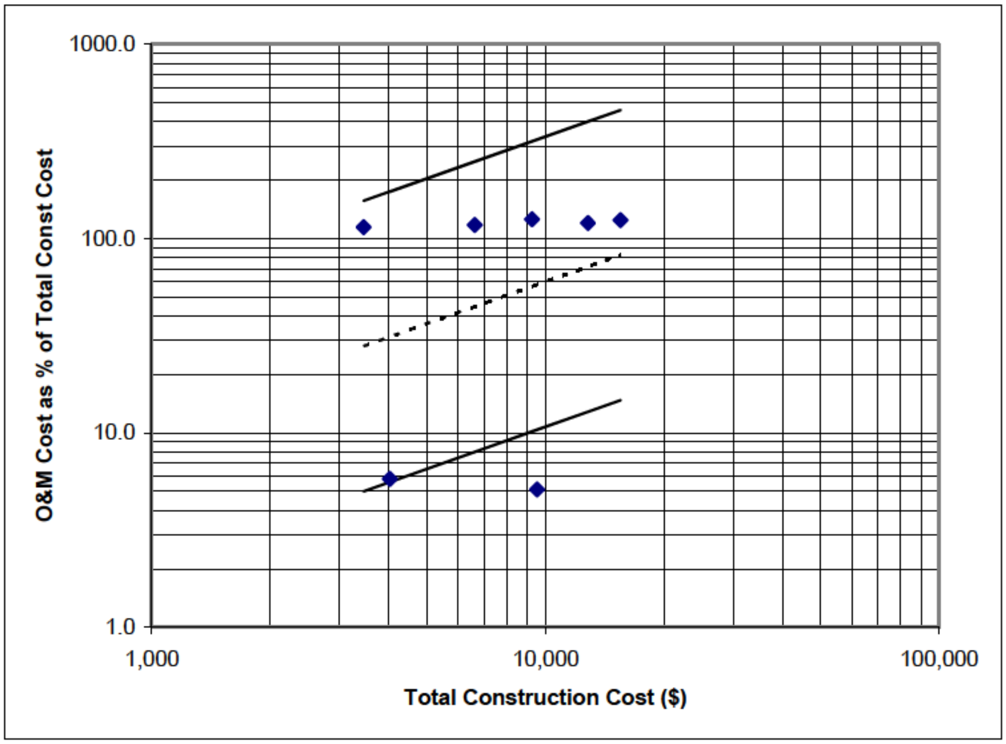

Figure 15. Annual O&M costs of infiltration trenches.

(Data from SWRPC, 1991; Landphair, *et al*, 2000)

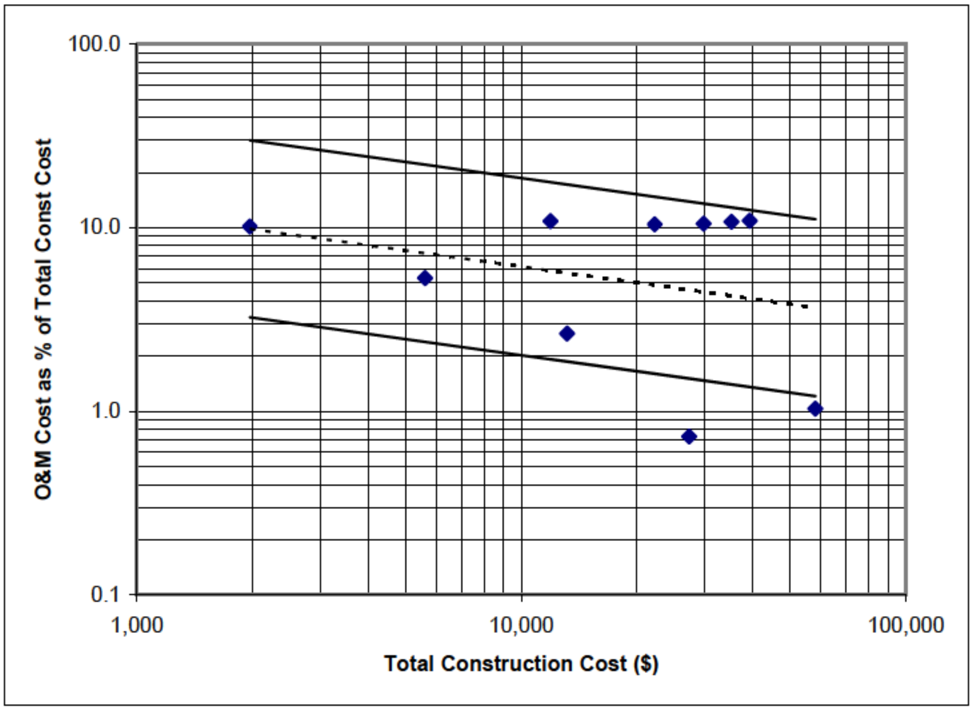

Figure 16. Annual O&M costs of bioinfiltration filters.

(Data from Landphair, *et al*, 2000; Wossink and Hunt, 2003)

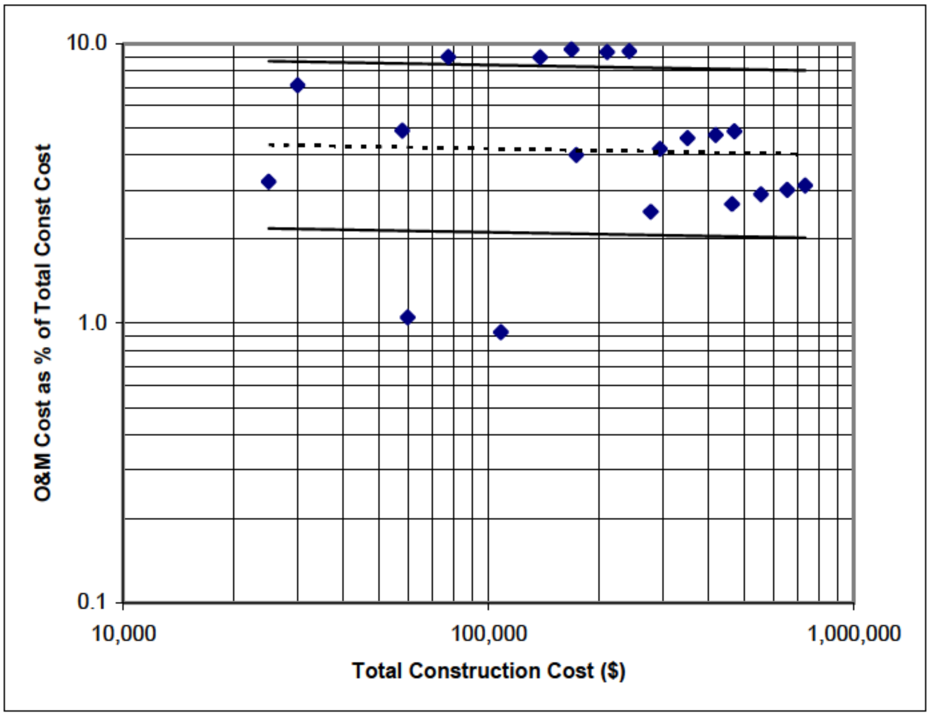

Figure 17. Annual O&M costs of sand filters.

(Data from Landphair, *et al*, 2000; Wossink and Hunt, 2003)

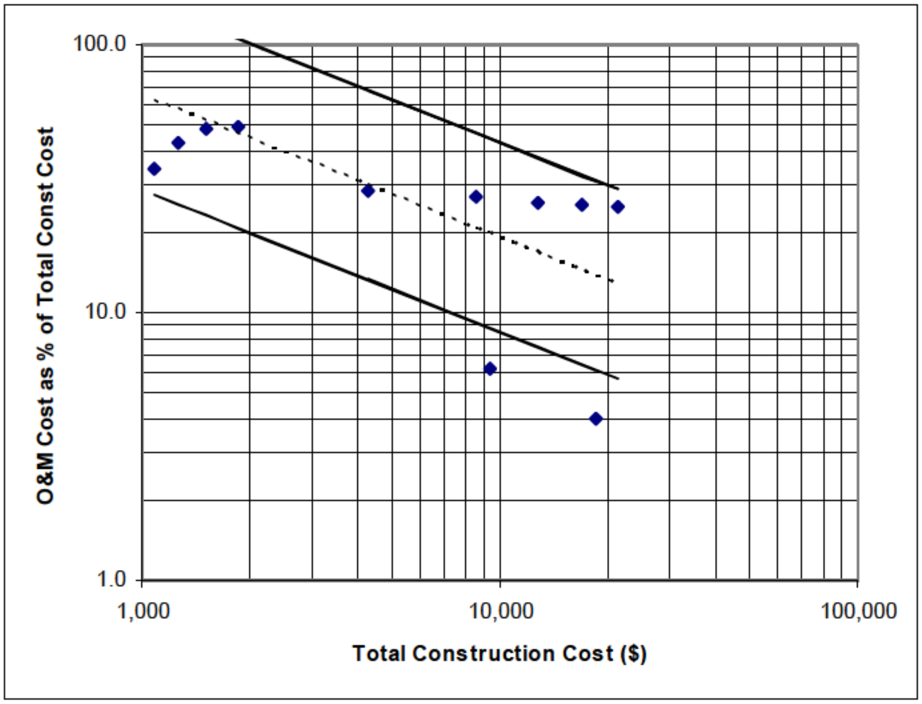

Figure 18. Annual O&M costs of grassed/vegetative swales.

(Data from Landphair, *et al*, 2000; SWRPC, 1991) order to estimate the Total Present Cost (TPC) of each SMP as a function of size. As previously defined, the TPC is the sum of the total construction cost and the equivalent present cost of 20 years of annual O&M expenses. For each SMP, the TPC is estimated as a function of size (*i.e.* WQV or swale top width).

The Total Present Cost with a 67% confidence interval for six of the seven SMPs was estimated as a function of water-quality volume (WQV). Also, the total present cost of a 1000' long grassed/vegetative swale was estimated as a function of the swale top width. The TPC estimates incorporate the total construction cost data and annual O&M cost data presented in the previous sections. In this estimate, the annual O&M costs are converted to an equivalent present cost using historical data on the rates of municipal bond yields and inflation. The analysis method and the results for each of the seven SMPs are presented below.

In order to estimate the TPC of each SMP the total construction cost was calculated as a function of size (*i.e.* WQV or swale top width) by multiplying the corresponding unit construction cost by WQV or, in the case of swales, by the swale length. Using these values of total construction cost and the annual O&M cost data best-fit line, the annual O&M cost was estimated for each WQV or swale top width. For example, for a dry detention basin, the unit construction costs for a range of WQVs were calculated from the best-fit line shown in Figure 6. The total construction costs were then estimated by multiplying the unit construction costs by the corresponding WQV. The annual O&M costs (as a percentage of construction cost) were then estimated using the best-fit line of Figure 12. Next, the value of the annual O&M cost estimates were calculated by multiplying each percentage (as found from the best-fit line) by the corresponding total construction cost. Finally, the annual O&M costs for a 20-year period were converted to an equivalent present cost (based on historical values of interest and inflation rates as described below) and added to the total construction cost.

Before the conversion of the annual O&M costs to an equivalent present cost is described, it must be noted that the annual O&M costs for infiltration trenches and grassed/vegetative swales were estimated in a different manner than described above. All but two of the O&M data points for these two SMPs (shown in Figures 15 and 18) were from Landphair, *et al* (2000) whose estimates ranged from 115 percent to 126 percent for infiltration trenches and 25 percent to 178 percent for grassed/vegetative swales. Since these values comprised most of the data and are high compared to the 5 percent to 20 percent for infiltration trenches and 5 percent to 7 percent for grassed/vegetative swales as summarized by the USEPA (1999a), a different method was applied when estimating these annual O&M costs. For infiltration trenches and grassed/vegetative swales, average values of the annual O&M cost (as a percent of total construction cost) based on the USEPA summary shown in Table 5 were assumed. Thus, annual O&M costs for infiltration trenches and grassed/vegetative swales were not determined from the best-fit line through the data, but rather assumed to be 12 percent (± 7%) and 6 percent (± 1%), respectively. Other than these assumptions, the TPC analysis for these two SMPs was identical to the others.

Returning to the method used to convert the annual O&M costs to an equivalent present cost and having obtained an annual O&M cost estimate, it was assumed that these costs would be incurred for 20 years. Based on this assumption, 20 years of annual O&M costs were converted to an equivalent present O&M cost using the time value of money and historical values of interest and inflation rates. Given an interest rate and inflation rate, the equivalent present cost of the 20-year annual O&M costs can be computed by an equation modified from Collier and Ledbetter (1988) which is:

$$P = C_{OM}\left[\frac{\left(\frac{1+r}{1+i}\right)^{n}-1}{r-i}\right] \tag{3}$$

Where: P = Equivalent present cost of 20-years of annual O&M costs

C_{OM} = annual O&M cost

r = inflation rate

i = interest rate

n = number of years (*i.e.* 20)

Equation 3 may be rewritten as:

$$P = C_{OM}\left[E\right] \tag{4}$$

where: $$E = \left[\frac{\left(\frac{1+r}{1+i}\right)^{n}-1}{r-i}\right]$$

Using average annual Aaa municipal bond yield rates (Mergent, Inc., 2003) for interest rate values and historical Consumer Price Index (CPI) based inflation rates (Fintrend.com, 2004), the value of E was calculated for each year from 1944 through 2002. Since this analysis is based on a 20-year time span, the running 20-year average value of E was calculated for each year from 1963 through 2002. The running 20-year average values are shown in Table 6 and resulted in an overall average value of 18.68 +/- 2.29 (67% confidence interval). Returning to the example and using a value of 18.68 for E, the present equivalent cost of 20 years of annual O&M expenses were calculated over the range of WQVs and added to the corresponding total construction cost to give the Total Present Cost (TPC) in 2005 dollars as a function of WQV. The uncertainties associated with the 67% confidence intervals of the unit construction costs, annual O&M costs as a percent of the construction cost, and inflation and interest rates (*i.e.* E) were incorporated into the TPC as described by Kline (1985).

Year	20-yr running Avg. E	Year	20-yr running Avg. E	Year	20-yr running Avg. E	Year	20-yr running Avg. E
1963	23.94	1973	17.55	1983	20.22	1993	18.23
1964	23.73	1974	18.25	1984	19.98	1994	17.41
1965	23.46	1975	18.68	1985	19.75	1995	16.91
1966	22.28	1976	18.74	1986	19.46	1996	16.74
1967	19.17	1977	18.82	1987	19.27	1997	16.36
1968	18.38	1978	19.02	1988	19.01	1998	15.93
1969	18.55	1979	19.80	1989	18.83	1999	15.12
1970	18.53	1980	20.56	1990	18.73	2000	14.32
1971	17.56	1981	20.66	1991	18.62	2001	14.12
1972	17.35	1982	20.46	1992	18.53	2002	14.27

Table 6. Yearly 20-year running average values of E.
(average of values shown is 18.68±2.29).

This method propagates the uncertainty found in each of the three above-mentioned variables (*i.e.* unit construction costs, annual O&M costs, and E) and determines the resulting uncertainty on the total present cost. Kline (1985) discusses two methods of calculating this uncertainty propagation; the first being a direct analytical solution and the second method being an approximate perturbation method. Since the unit-construction cost data is linear on a log-log plot, the linear regression through the data which gave the best-fit line was performed on the log of the unit construction costs and log of the water quality volume. Therefore, the corresponding uncertainty was also based on the log of the data and the uncertainty of the unit-cost values was estimated from this uncertainty. More specifically, the uncertainty of the unit-construction costs was estimated by raising 10 to the α power where α equals the uncertainty on the log of the data. This estimation dictated that the perturbation method be employed rather than the direct analytical solution.

The Total Present Cost (with 67% confidence interval), excluding land costs, of each SMP is shown on log-log plots as a function of WQV or swale top width in Figures 19 through 25. The range of water quality volumes for each SMP shown in these figures corresponds to the range for which construction cost data was obtained. These figures are based on historical data and are intended to be used for comparative purposes only. They are not intended to estimate costs associated with specific SMPs nor should cost be the only factor considered when selecting a SMP.

Effectiveness of Contaminant Removal

Undoubtedly an estimate of the total cost of a SMP can be a valuable aid during the planning and selection process. However, an inexpensive SMP that has minimal impact on water quality would be of little value. Thus, knowledge of the impact or effectiveness a particular

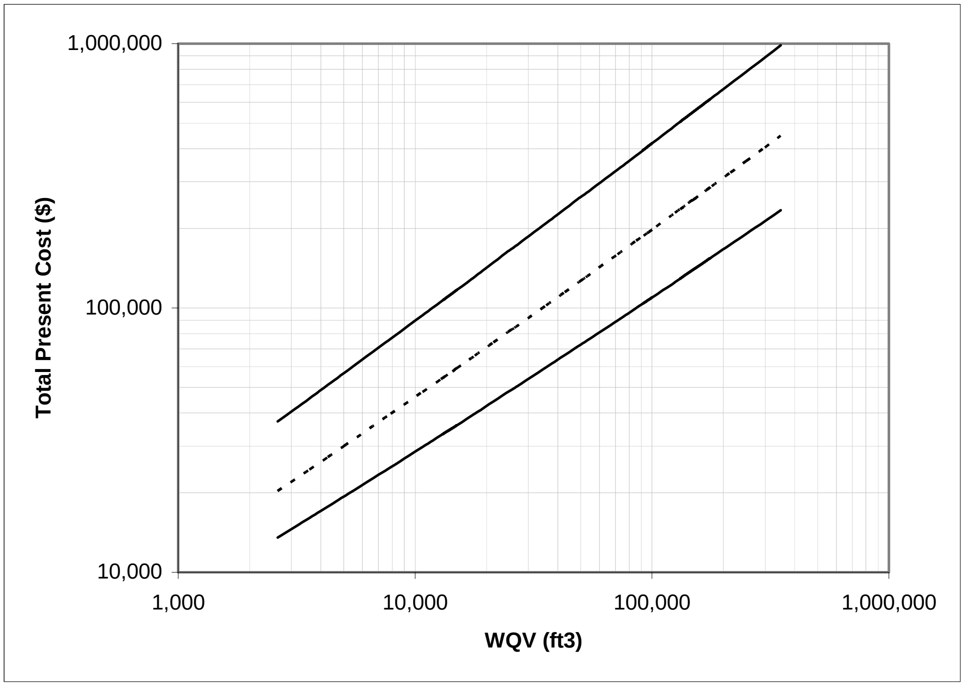

Figure 19. Total Present Cost (TPC) of dry detention basins with 67% CI. Land costs are excluded and need to be determined separately.

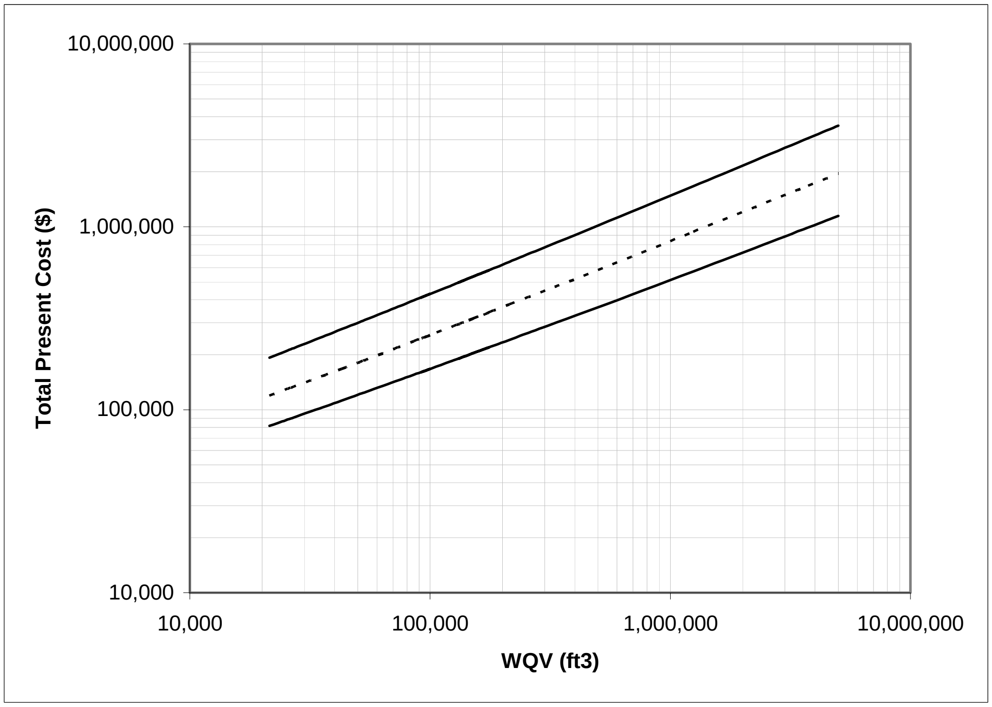

Figure 20. Total Present Cost (TPC) of wet basins with 67% CI. Land costs are excluded and need to be determined separately.

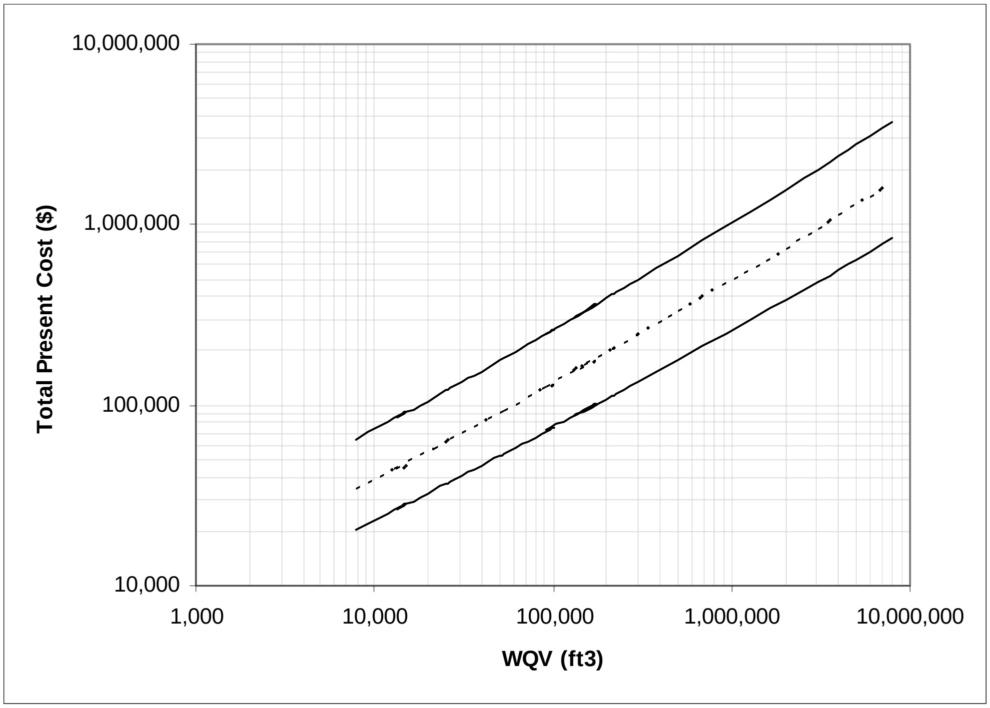

Figure 21. Total Present Cost (TPC) of constructed wetlands with 67% CI. Land costs are excluded and need to be determined separately.

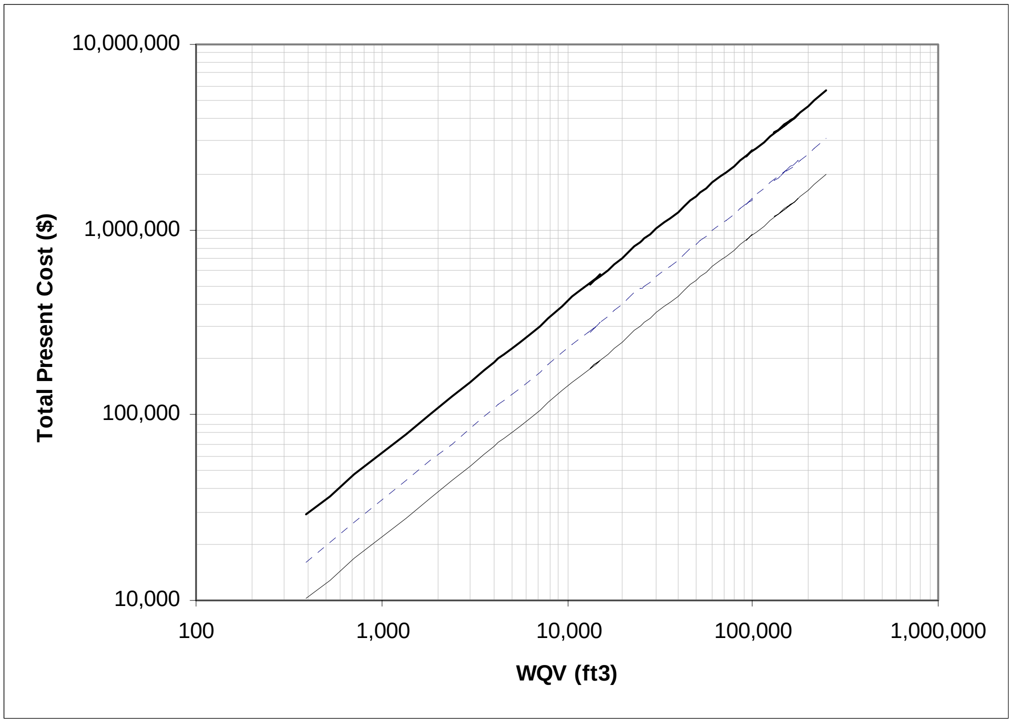

Figure 22. Total Present Cost (TPC) of infiltration trenches with 67% CI. Land costs are excluded and need to be determined separately.

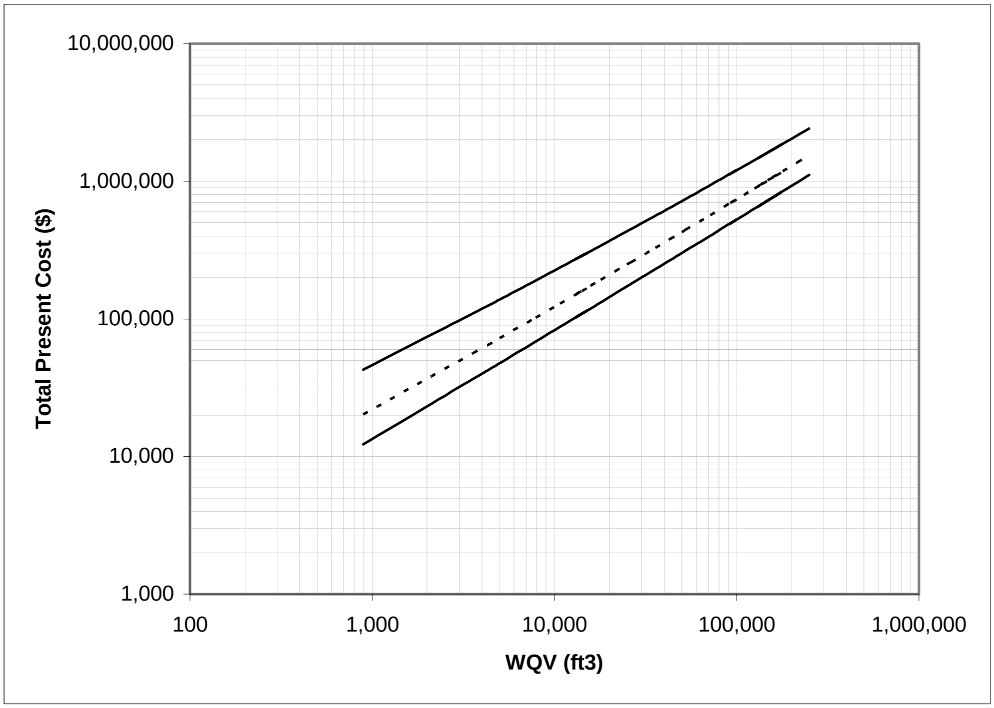

Figure 23. Total Present Cost (TPC) of bioinfiltration filters with 67% CI. Land costs are excluded and need to be determined separately.

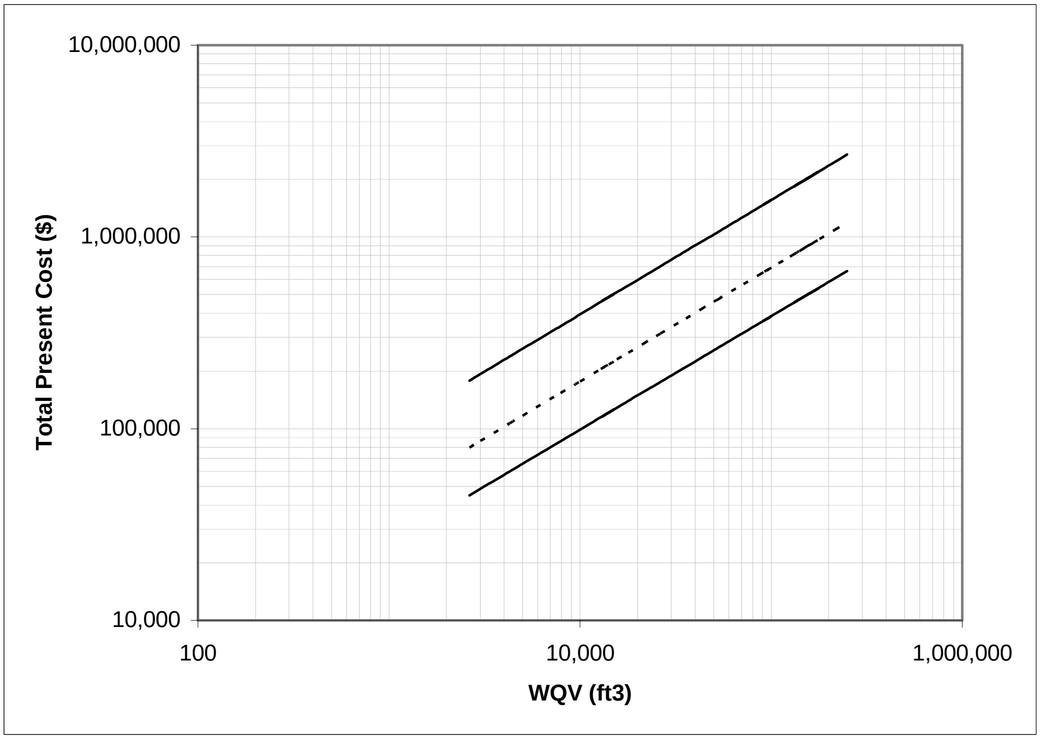

Figure 24. Total Present Cost (TPC) of sand filters with 67% CI. Land costs are excluded and need to be determined separately.

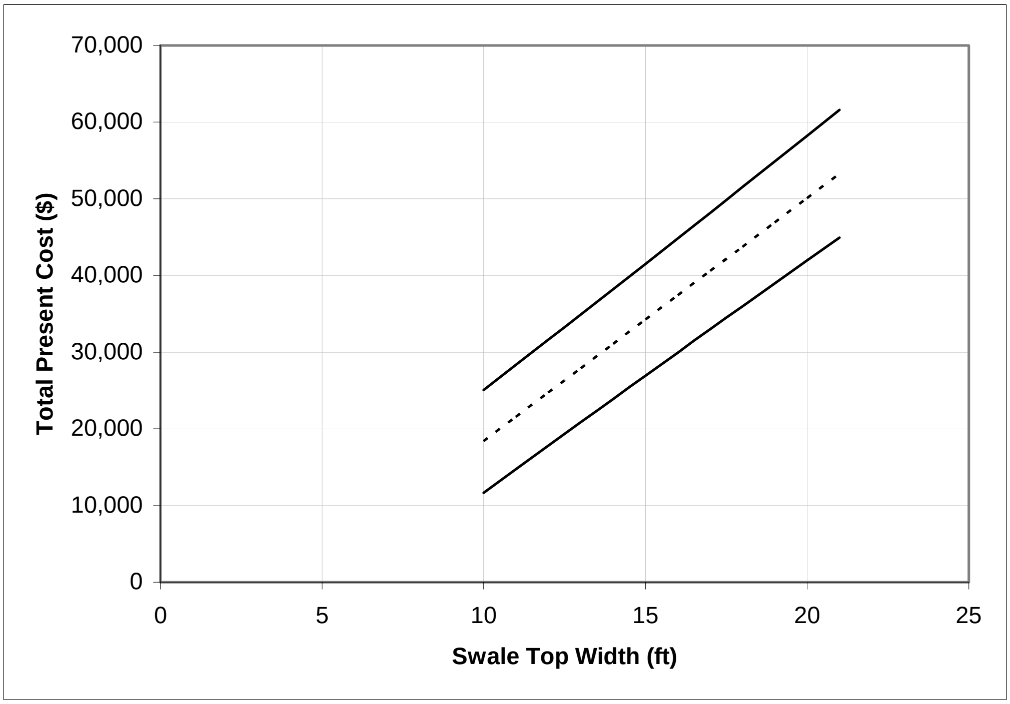

Figure 25. Total Present Cost (TPC) of 1000' long grassed/vegetative swales with 67% CI. Land costs are excluded and need to be determined separately.

SMP will have on water quality is just as important as the cost. In an effort to provide information in this area, an analysis was performed in which the total amount of TSS and phosphorus removed over a 20-year span was estimated as a function of water-quality volume. In this analysis the amount of TSS and P removed is considered to be a function of the fraction of stormwater runoff that will be treated by the SMP, the pollutant load which reaches the SMP, and the removal performance of the SMP itself. Of course, some of the variables listed above depend on other variables such as watershed area, impervious area, rainfall amounts, etc. All of these variables and the analytical method which was used to incorporate them into the estimate of total pollutant load removal is described and discussed below.

Runoff Fraction Treated

Most SMPs are designed for a particular rainfall depth used to estimate a water-quality volume or, in the case of swales, filter strips, and similar SMPs, a peak flow rate. The WQV or peak flow rate is used to size the SMP. Since an SMP is designed for a finite value of rainfall and/or runoff, there is always the chance that a given storm will produce more runoff than the unit was designed to store and/or treat. When that happens, a portion of the runoff bypasses the SMP or is discharged from the SMP via an overflow outlet and receives no treatment. In order to account for this untreated fraction of the runoff, a statistical analysis was performed on historical rainfall data in the Twin Cities. Given the design rainfall depth, the process, as described below, can be used to estimate the fraction of stormwater runoff that will be bypassed or exit the SMP without treatment.

Since design recommendations for SMPs usually state that the devices should be designed to drain in two days, two-day running sum precipitation amounts in the Twin Cities were calculated and analyzed from 1950 through 2003. For example, if the precipitation depths measured on four consecutive days were 0.21 in., 0.13 in., 0.35 in., and 0.07 in., the data would be combined into two-day precipitation amounts of 0.34 in., 0.48 in., and 0.42 in., respectively. Using the combined data, a two-day running sum (R_S) histogram was generated using 0.10 inch increments from zero to four inches, with the last bin including any two-day sum that was greater than or equal to four inches. Of the 9,720 non-zero entries, five fell into the latter category, with the largest having a value of 10.00 inches. Columns 1 through 4 of Table 7 show the histogram in tabular form along with the frequency and cumulative frequency distributions. Subtracting the cumulative frequency from 1.00 and multiplying by 100 gives the percent exceedance as shown in column 5 and plotted in Figure 26.

Thus Table 7 and/or Figure 26 can be used to determine the fraction of two-day precipitation events that exceeded a particular precipitation depth. For example, based on Figure 26, a two-day rainfall depth of 1.00 inch was exceeded approximately 7 percent of the time over the 54-year period analyzed. Alternatively, using Table 7 and linearly interpolating between 7.43% and 6.24% gives a value of 6.84% exceedance for a precipitation depth of one inch. Furthermore, if an SMP were designed for a precipitation depth of 1.00 inch, the graph area that is both under the curve **and** below the horizontal line that corresponds to an abscissa value of 1.00 inch divided by the total area under the curve, equals the fraction of the two-day summed precipitation amounts that were below the 1.00 inch design storm depth. The values of the graph area, cumulative area, and percent of total area corresponding to each precipitation depth have been calculated and are shown in columns 6, 7, and 8, respectively, of Table 7. Due to infiltration and other abstractions of the stormwater which occur as the runoff makes it way to the SMP, this ratio is not exactly the fraction of runoff that would be treated by the SMP. That

(1) Range (in.)	(2) # of events	(3) Frequency	(4) Culm. Frequency	(5) % exceedance	(6) Area (in)	(7) Culm. Area (in)	(8) % of Total Area	(9) Rainfall Depth (in)
				100.00			0.00	0.00
0<Rs<0.1	4037	0.41533	0.41533	58.47	3.962	3.962	13.88	0.05
0.1<=Rs<0.2	1599	0.16451	0.57984	42.02	5.024	8.986	31.48	0.15
0.2<=Rs<0.3	965	0.09928	0.67912	32.09	3.705	12.691	44.45	0.25
0.3<=Rs<0.4	683	0.07027	0.74938	25.06	2.858	15.549	54.46	0.35
0.4<=Rs<0.5	501	0.05154	0.80093	19.91	2.248	17.797	62.34	0.45
0.5<=Rs<0.6	377	0.03879	0.83971	16.03	1.797	19.594	68.63	0.55
0.6<=Rs<0.7	276	0.02840	0.86811	13.19	1.461	21.055	73.75	0.65
0.7<=Rs<0.8	250	0.02572	0.89383	10.62	1.190	22.245	77.92	0.75
0.8<=Rs<0.9	171	0.01759	0.91142	8.86	0.974	23.219	81.33	0.85
0.9<=Rs<1.0	139	0.01430	0.92572	7.43	0.814	24.033	84.18	0.95
1.0<=Rs<1.1	115	0.01183	0.93755	6.24	0.684	24.717	86.58	1.05
1.1<=Rs<1.2	99	0.01019	0.94774	5.23	0.574	25.290	88.59	1.15
1.2<=Rs<1.3	98	0.01008	0.95782	4.22	0.472	25.763	90.24	1.25
1.3<=Rs<1.4	65	0.00669	0.96451	3.55	0.388	26.151	91.60	1.35
1.4<=Rs<1.5	58	0.00597	0.97047	2.95	0.325	26.476	92.74	1.45
1.5<=Rs<1.6	46	0.00473	0.97521	2.48	0.272	26.748	93.69	1.55
1.6<=Rs<1.7	34	0.00350	0.97870	2.13	0.230	26.978	94.50	1.65
1.7<=Rs<1.8	*27*	0.00278	0.98148	1.85	0.199	27.177	95.20	1.75
1.8<=Rs<1.9	*20*	0.00206	0.98354	1.65	0.175	27.352	95.81	1.85
1.9<=Rs<2.0	18	0.00185	0.98539	1.46	0.155	27.507	96.35	1.95
2.0<=Rs<2.1	18	0.00185	0.98724	1.28	0.137	27.644	96.83	2.05
2.1<=Rs<2.2	16	0.00165	0.98889	1.11	0.119	27.764	97.25	2.15
2.2<=Rs<2.3	14	0.00144	0.99033	0.97	0.104	27.868	97.62	2.25
2.3<=Rs<2.4	16	0.00165	0.99198	0.80	0.088	27.956	97.93	2.35
2.4<=Rs<2.5	9	0.00093	0.99290	0.71	0.076	28.032	98.19	2.45
2.5<=Rs<2.6	9	0.00093	0.99383	0.62	0.066	28.098	98.42	2.55
2.6<=Rs<2.7	10	0.00103	0.99486	0.51	0.057	28.155	98.62	2.65
2.7<=Rs<2.8	8	0.00082	0.99568	0.43	0.047	28.202	98.79	2.75
2.8<=Rs<2.9	8	0.00082	0.99650	0.35	0.039	28.241	98.92	2.85
2.9<=Rs<3.0	8	0.00082	0.99733	0.27	0.031	28.272	99.03	2.95
3.0<=Rs<3.1	5	0.00051	0.99784	0.22	0.024	28.296	99.12	3.05
3.1<=Rs<3.2	5	0.00051	0.99835	0.16	0.019	28.315	99.18	3.15
3.2<=Rs<3.3	2	0.00021	0.99856	0.14	0.015	28.331	99.24	3.25
3.3<=Rs<3.4	2	0.00021	0.99877	0.12	0.013	28.344	99.28	3.35
3.4<=Rs<3.5	2	0.00021	0.99897	0.10	0.011	28.355	99.32	3.45
3.5<=Rs<3.6	0	0.00000	0.99897	0.10	0.010	28.365	99.36	3.55
3.6<=Rs<3.7	2	0.00021	0.99918	0.08	0.009	28.375	99.39	3.65
3.7<=Rs<3.8	2	0.00021	0.99938	0.06	0.007	28.382	99.42	3.75
3.8<=Rs<3.9	1	0.00010	0.99949	0.05	0.006	28.388	99.44	3.85
3.9<=Rs<4.0	0	0.00000	0.99949	0.05	0.005	28.393	99.45	3.95
4.0<=Rs	5	0.00051	1.00000	0.00	0.156	28.548	100.00	10.00

# of Events= 9720

Total Area= 28.548

Table 7. Statistical analysis of historical 2-day precip. amounts at the MPLS-St. Paul airport.

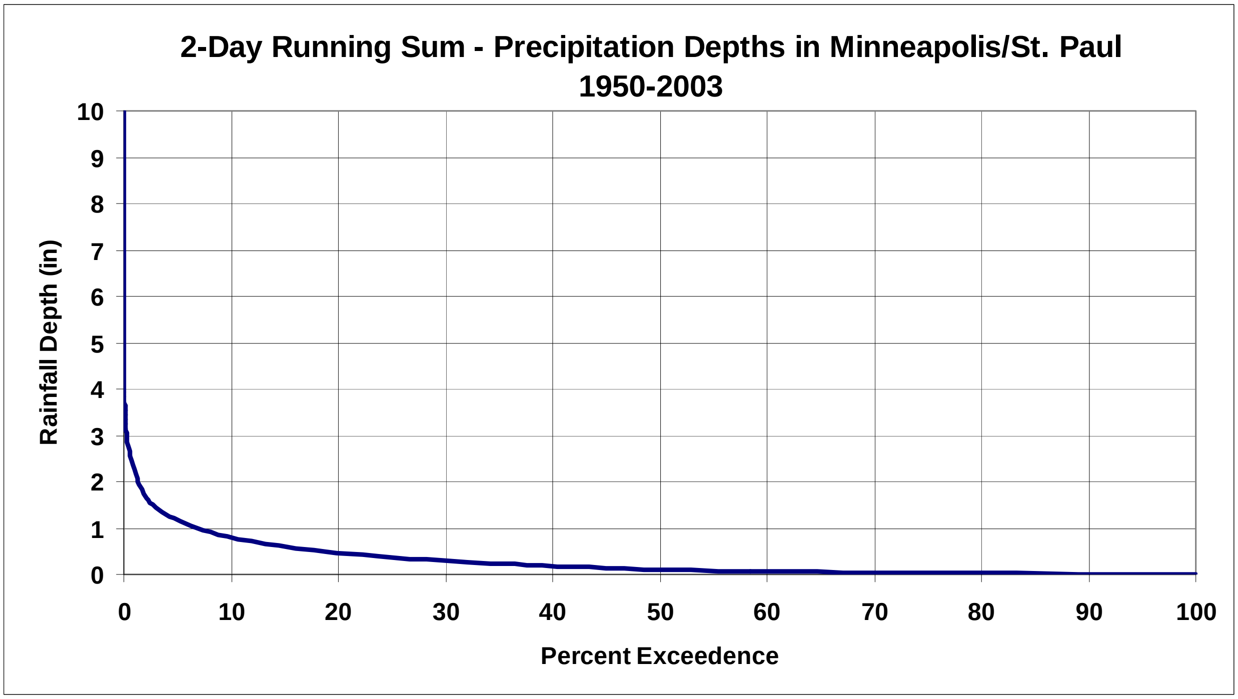

Figure 26. Exceedance probabilities of two-day precipitation depths in the Twin Cities.

would only be the case if 100 percent of the precipitation were to reach the SMP as runoff. However, the percent of total area values shown in column 8 can be used as an approximate estimate of the fraction of runoff that would be treated by an SMP designed for the corresponding rainfall depth in column 9. For example, based on columns 8 and 9 of Table 7, if an SMP was designed for a precipitation depth of 2.25 inches, it could be estimated that, based on historical data, the SMP would treat 97.62 percent of the stormwater runoff over time.

For the purposes of this report it was assumed that all SMPs would be designed for a precipitation depth of 1.45 inches which is approximately the three-month, 24-hour storm for the Twin Cities metro region (Huff and Angel, 1992). As shown in Table 7, a depth of 1.45 inches corresponds to approximately 93 percent of the area under the curve. As discussed above, it was estimated that 93 percent of all stormwater runoff will be treated by an SMP which is designed for the volume of runoff corresponding to this precipitation depth. Thus, when estimating the total amount of TSS and P removed over 20 years, it was assumed that 93 percent of all stormwater runoff will be treated by the SMPs and the remaining 7 percent of the runoff will receive no treatment. Thus, total suspended sediment and phosphorus removal are given by:

$$\%\text{Total Removal} = 0.93 * \left(\%\text{Removal by SMP}\right) \tag{5}$$

where the “%Removal by SMP” is the removal based on inflow and treated outflow concentrations and does not consider overflow conditions. Overflow and/or bypass conditions are accounted for by multiplying the “%Removal by SMP” by 0.93.

Pollutant Loading

Several methods with a wide degree of complexity are available to estimate stormwater pollutant loads. For example, the Stormwater Management Model (SWMM) is public domain software and can be used to model single storm events or watershed basins over time. Additional methods described Young, *et al*. (1995) include regional United States Geological Survey (USGS) equations for estimation of storm loads, runoff volumes, and event mean concentrations. These equations have been developed for three regions in the United States and are based on regression analysis of nationwide data. A simplified, but less accurate, set of USGS regression equations are also available and can be used to estimate storm runoff loads and volumes. The USGS has also derived a set of equations to estimate storm mean concentrations and mean seasonal or annual loads.

The Federal Highway Administration (FHWA) has developed a method to estimate pollutant loading from highway runoff (Driscoll, *et al*., 1990). As with the USGS methods, the FHWA method is a regional method, in this case with nine regions, which involves a relatively large amount of detailed input to arrive at an estimate of annual pollutant mass loading.

The methods described above require a level of detail that is well beyond what is necessary (or perhaps possible) for the comparative purposes of this report. Thus, for this report, a modified version of a less involved method, the Simple Method, was selected to estimate pollutant loads. The Simple Method, first proposed by Schueler (1987), is widely accepted and requires only the mean annual precipitation, percent of rainfall events that produce no runoff, the drainage area, and a runoff coefficient be known. The modified Simple Method used in this report is used by the Lower Colorado River Authority (1998) and has been recommended for use by the State of Texas, Department of Transportation (Landphair, *et al.*, 2000). In its modified form, the simple method is:

$$\mathrm{L} = (0.2266) * \mathrm{A} * \mathrm{R}_{\mathrm{F}} * \mathrm{R}_{\mathrm{V}} * \mathrm{C} \qquad (6)$$

where: L = Annual pollutant load (lb.)

A = Watershed area (acre)

R_F = Average annual rainfall (in.)

R_V = Average annual runoff coefficient (*i.e.* runoff:rainfall ratio)

C = Average annual contaminant (*i.e.* TSS & P) concentration (mg/L)

The runoff coefficient R_V, was described for water quality volume calculations and is estimated as:

$$\mathrm{R}_{\mathrm{V}} = 0.05 + 0.009 * (\mathrm{I}) \qquad (2)$$

where: I = Percent of watershed that is impervious

In order to coincide with the 20-year time span used to estimate the total present cost, the pollutant loading must also be estimated for 20 years. To accomplish this, Equation 5 must be multiplied by 20. Also, the variable R_F, must no longer be defined as the average annual rainfall but rather, the 20-year running average of annual rainfall (inches). Incorporating these small but significant changes, the equation used to estimate the TSS and P loading over a 20-year span becomes:

$$L_{20} = 20 * 0.2266 * A * R_{F20} * R_V * C \tag{7}$$

Where: L_{20} = Estimated pollutant load over 20 years (lb.)

R_{F20} = 20-year running average of annual rainfall (in.)

and all other variables are as previously defined.

For the purposes of this report it was assumed that the watershed area A, percent impervious I, and therefore the runoff coefficient R_V, would be known without any uncertainty. To obtain an estimate of R_{F20}, a statistical analysis on historical precipitation data in Minneapolis and St. Paul from 1950 through 2003 was performed. The results showed that the 20-year running average precipitation depth is 28.44 inches +/- 1.80 inches (67% confidence interval).

In order to determine estimates of the average annual concentration of TSS and P in stormwater runoff, data was compiled from several studies and dozens of sites (Moxness, 1986; Moxness, 1987; Moxness, 1988; Driscoll, *et al.*, 1990; Oberts, 1994; Barrett, *et al.*, 1995; Stanley, 1996; Wu, J.S., *et al.*, 1996; Sansalone and Buchberger, 1997; Barrett, *et al.*, 1998; Anderle, T.A., 1999; Legret and Colandini, 1999; Waschbusch, *et al.*, 1999; Carleton, *et al.*, 2000; Drapper, *et al.*, 2000; Brezonik and Stadelmann, 2002; Harper, *et al.*, undated). Data analysis revealed that the average values of stormwater concentrations of TSS and P from sites located in the Twin Cities were essentially the same as average values of all other sites located throughout the nation and Australia. Since the data was similar, the national average values of 131 mg/L +/- 77 mg/L (67% confidence interval) for TSS and 0.55 mg/L +/- 0.41 mg/L (67% confidence interval) for total P were used. With values for R_{F20} and C estimated, the total pollutant load for TSS and P in pounds over a 20-year time frame, as estimated by Equation 7, becomes a function of only two variables; watershed area and, with the use of Equation 2, the percent of the watershed area that is impervious.

With the selection of a storm design depth of 1.45" as previously discussed, the two remaining variables that determine the 20-year pollutant loads (*i.e.* watershed area and percent impervious) are also the same two variables that determine the WQV. Thus, for a watershed of known area and percent impervious, both the WQV and the TSS and P loads over 20 years can be estimated. In other words, for a given watershed, each value of WQV corresponds to a unique value of 20-year TSS and P loads. While pollutant loading is certainly important, the intent of this analysis is to estimate the load removed by the SMPs over a 20-year span. As with the Total Present Cost (TPC), the estimate of the pollutant load removed by each SMP will be estimated as a function of WQV. Before this analysis can be completed, however, one remaining variable, the percent of TSS and P removed by each category of SMPs, must be estimated.

Fraction of Contaminants Removed

With the fraction of runoff treated and the total 20-year pollutant load estimated, the remaining variable that must be estimated is the fraction of TSS and P removed by each type of SMP (*i.e*. "%Removal by SMP" in Equation 5). Once the removal rate of each SMP has been estimated, the total mass of TSS and P removed over the 20-year span may be estimated by multiplying the 20-year pollutant load by both the fraction of runoff treated (i.e. estimated to be 93% for a design precipitation of 1.45 inches) and the fraction of pollutant removed by the SMP. The fraction of TSS and P removed is usually reported in one of two ways; as a percent change between influent and effluent concentrations or as the percent change between the total mass load entering the SMP and the mass load exiting the SMP. Most of the data obtained were based on concentrations, however some values of reported removal rates were not clearly defined.

In order to make the estimate of SMP removal performance (*i.e.* %Removal SMP in Equation 5) as realistic as possible, published data on the performance of the various types of SMPs analyzed in this study was collected and the average removal rate with 67% confidence interval calculated. Only data from actual sites which were field tested were included. When a single site was monitored over time and had more than one removal rate reported, only the average value of the data for that site was included in the analysis.

Ideally, the estimate of total contaminant load removed over 20 years would be based on data reported as the percent of total mass load removed. However, due to limited data of this kind, this analysis combined removal rates based on mass load removed and removal rates based on the percent change in contaminant concentration between inflow to the SMP and treated outflow from the SMP. For each type of SMP the average percent removal of the combined data was calculated and assumed to be the average percent of mass load removed. When accounting for infiltration of stormwater which may occur inside some SMPs (*e.g.* wetlands, dry basins, etc.), the percent drop in the influent to effluent concentration should be smaller than the percent of mass load removed. Thus, by combining concentration-based removal rates with those based on mass loads and assuming the resulting average to be the percent of mass load removed is a conservative one.

The results are summarized in Table 8 below and the full data is included in Appendix B. Sufficient amounts of reliable data which are needed to estimate the TSS removal rate of bioretention filters and TSS and phosphorus removal rates of infiltration trenches were not available. As denoted by the asterisks in Table 8, typical values of 90 percent and 75 percent for TSS removal (for bioretention filters and infiltration trenches, respectively) as reported by the Idaho BMP Manual (undated), were used. Also assumed was the Idaho BMP Manual typical infiltration trench phosphorus removal of 55%. The assumed values for TSS removal were either in agreement with other reported typical ranges of effectiveness, or conservative as Caltrans (2004) assumed infiltration trenches and basins remove 100 percent of TSS. Some literature, such as Caltrans (2004), have reasoned that since any water entering these SMPs is removed from the surface water, these SMPs achieve 100% removal of TSS and P. However, some dissolved contaminants may potentially reach the groundwater (MPCA, 2000) and could reenter as surface water at a later time. If this were to occur, the actual TSS and phosphorus removal of some SMPs would be less than 100%. The 67% confidence interval for these SMPs were also assumed and are denoted by an asterisk in Table 8.

SMP	%TSS Removal	TSS 67% CI	% P Removal	P 67% CI
Dry Detention Basins	53	±28	25	±15
Wet Basins	65	±32	52	±23
Stormwater Wetland	68	±25	42	±26
Bioretention Filter	90*	±10*	72	±11
Sand Filter	82	±14	46	±21
Infiltration Trench	75*	±10*	55*	±35*
Filter Strips/Grassed Swales	75	±20	41	±33

Table 8. Average percent removal rates of SMPs with corresponding confidence interval.

(* denotes assumed value)

As previously discussed, the published data used to calculate the values shown in Table 8 were reported in either percent drop in concentration between influent and effluent stormwater or percent removal of the total mass load entering the SMP. The values are based only on stormwater treated by the SMP and do not account for any portion of the flow that bypasses the SMP or exits through an overflow outlet. The confidence intervals reported in Table 8 reveal a large amount of uncertainty in the reported data. The uncertainty is likely due to variations in design and maintenance of the SMPs. If proper maintenance is not performed, removal levels will drop. Also, parameters such as swale slope, pond and wetland residence time, etc. affect removal.

The total amount of TSS that can be expected to be removed by each SMP (except for grassed/vegetative swales) was calculated by multiplying the 20-year total TSS load by 93 percent (*i.e.* estimated percent of runoff treated) and by the corresponding removal rate as shown in Table 8. The results, with a 67% confidence interval, are shown as a function of WQV in Figures 27 through 32 below. Similarly, the amounts of phosphorus that can be expected to be removed from the various SMPs are shown in Figures 33 through 38. As with the Total Present Cost graphs, the contaminant removal estimates are shown on a log-log scale where appropriate. Also, uncertainties in contaminant concentration, 20-year running average precipitation, and percent of contaminant removal by the SMPs were incorporated by the direct analytical method described by Kline (1985).

Since swales are designed for a peak flow rate and not WQV, an estimate of the total load removed by swales over 20 years could not be estimated as a function of WQV. However, if the volume of runoff which will be treated by a swale can be estimated, the removal rates reported in Table 8 for Filter Strips/Grassed Swales may be used to estimate the corresponding total contaminant load removed.

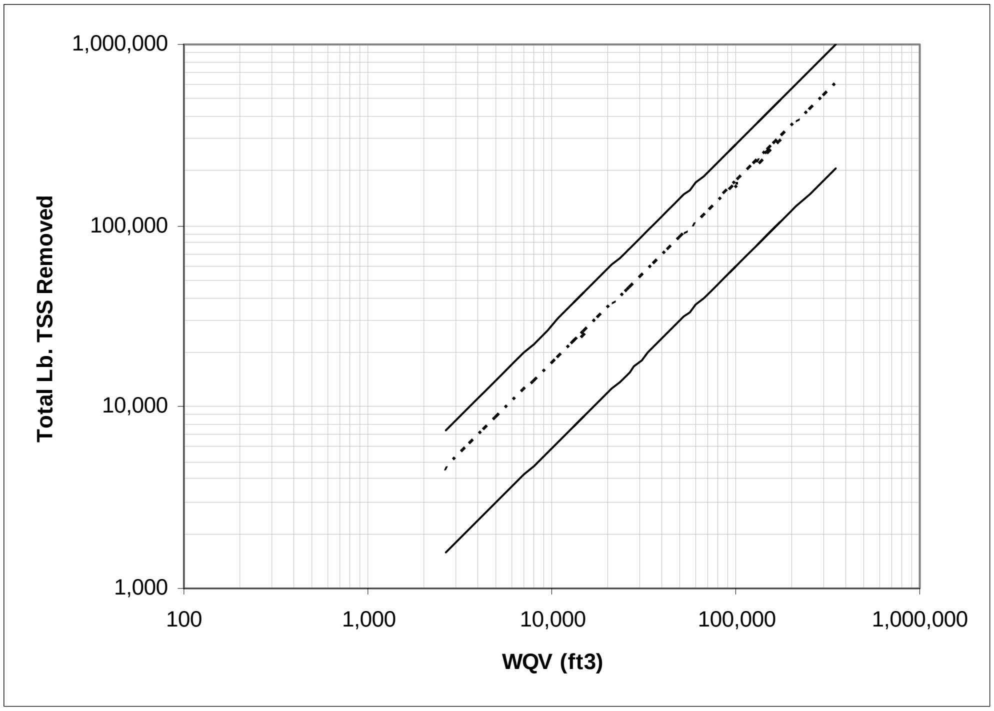

Figure 27. Estimated TSS removed in 20 years for dry detention basins with the 67% CI.

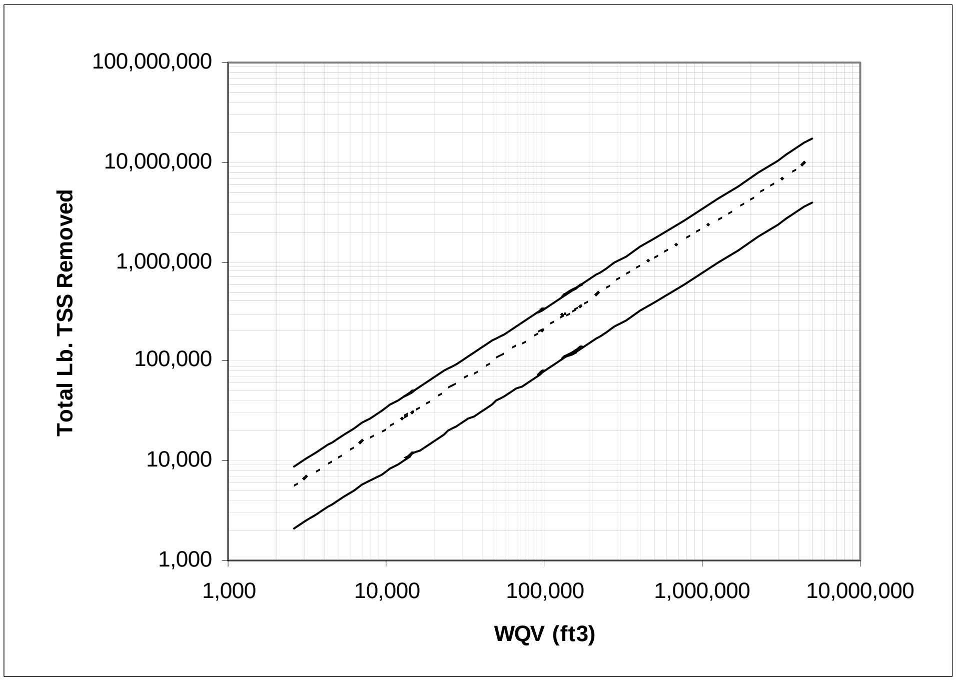

Figure 28. Estimated TSS removed in 20 years for wet basins with the 67% CI.

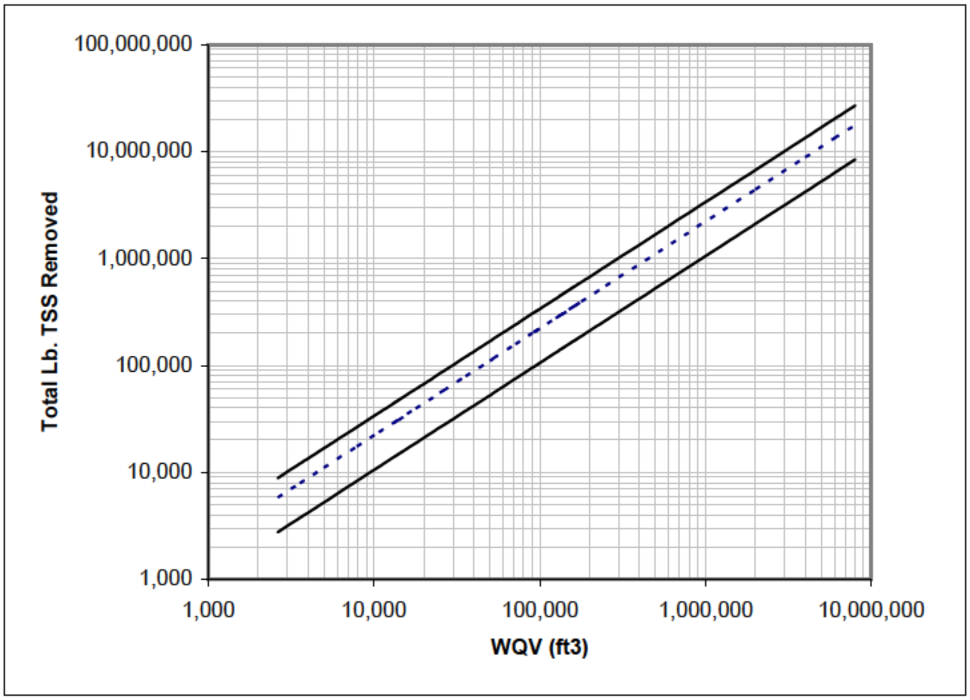

Figure 29. Estimated TSS removed in 20 years for constructed wetlands with the 67% CI.

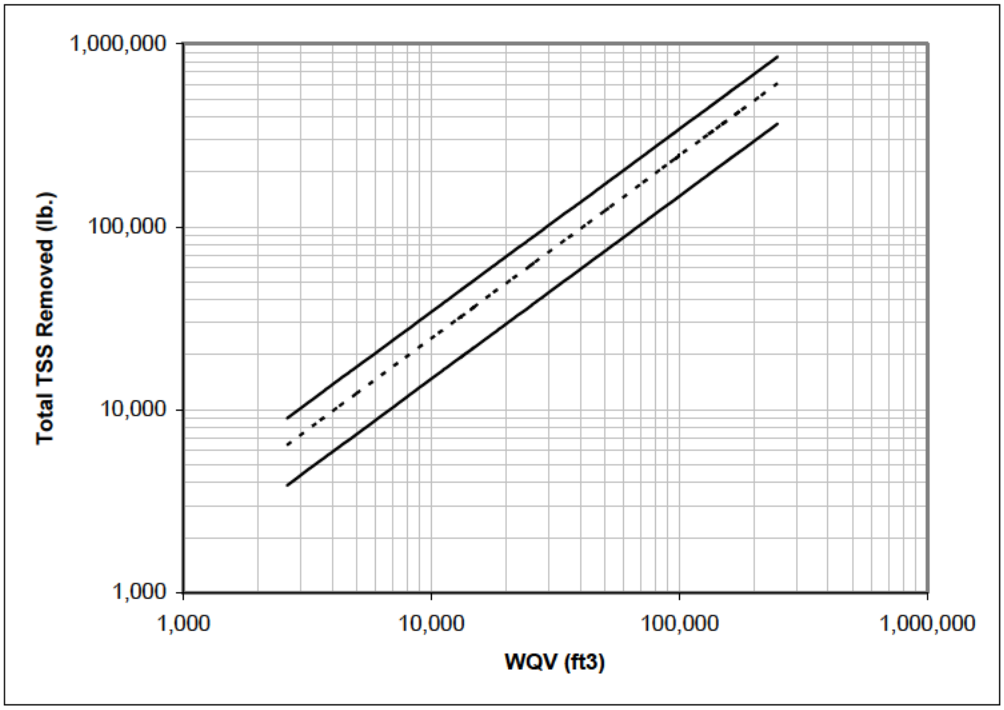

Figure 30. Estimated TSS removed in 20 years for infiltration trenches with the 67% CI.

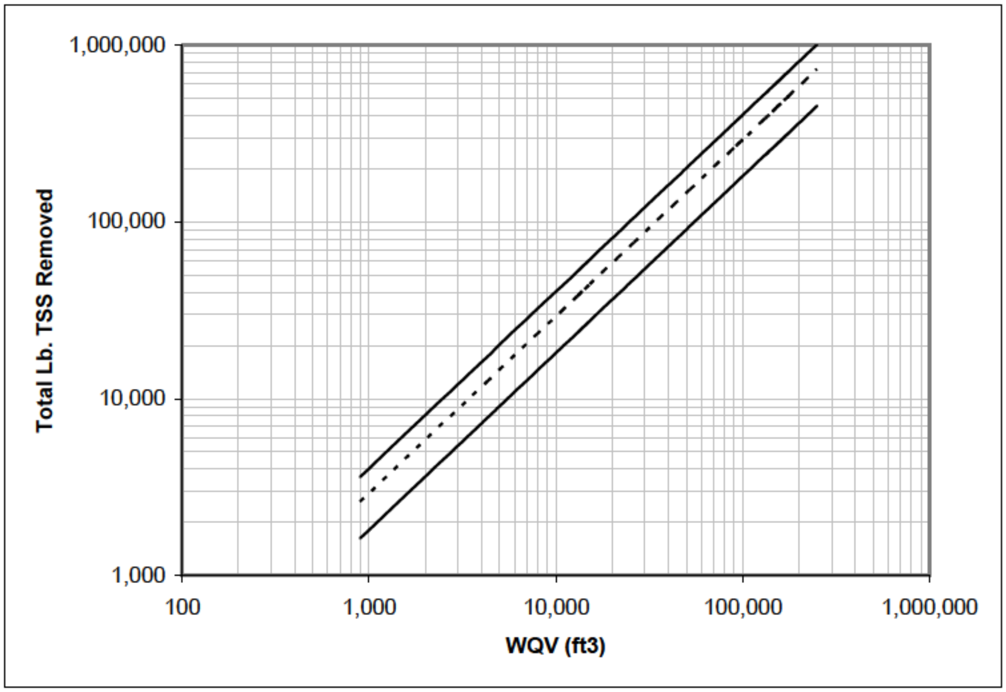

Figure 31. Estimated TSS removed in 20 years for bioinfiltration filters with the 67% CI.

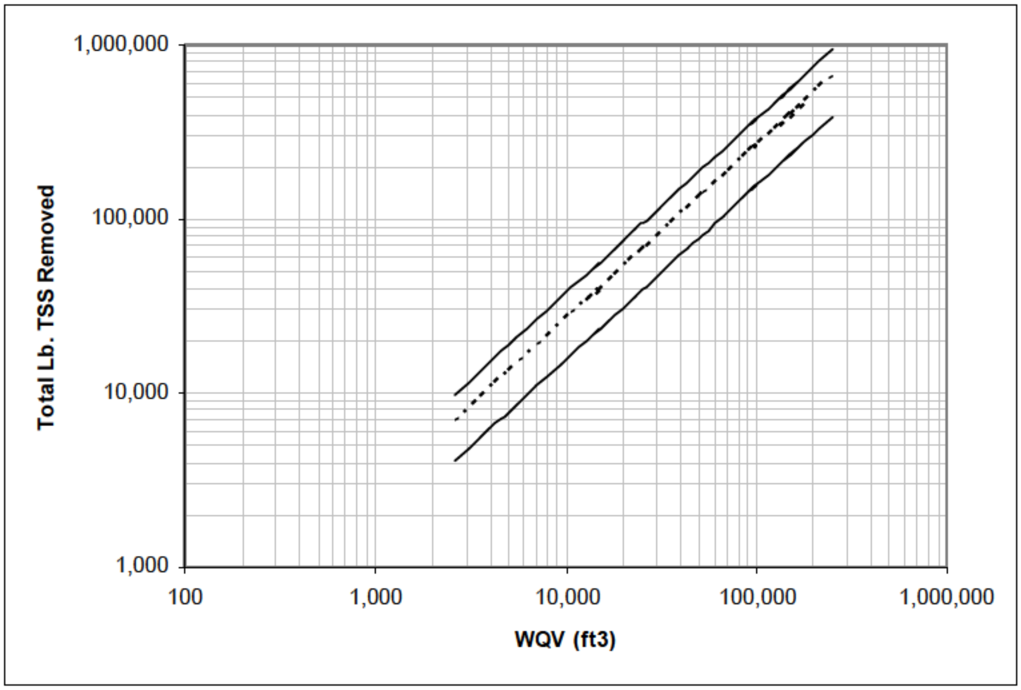

Figure 32. Estimated TSS removed in 20 years for sand filters with the 67% CI.

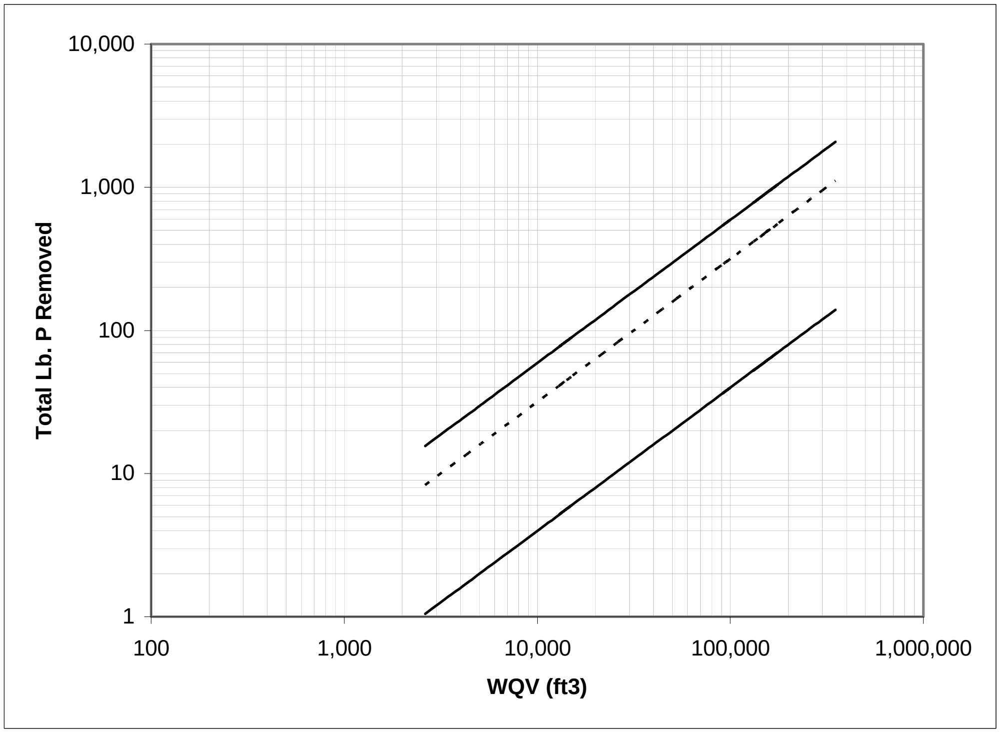

Figure 33. Estimated P removed in 20 years for dry detention basins with the 67% CI.

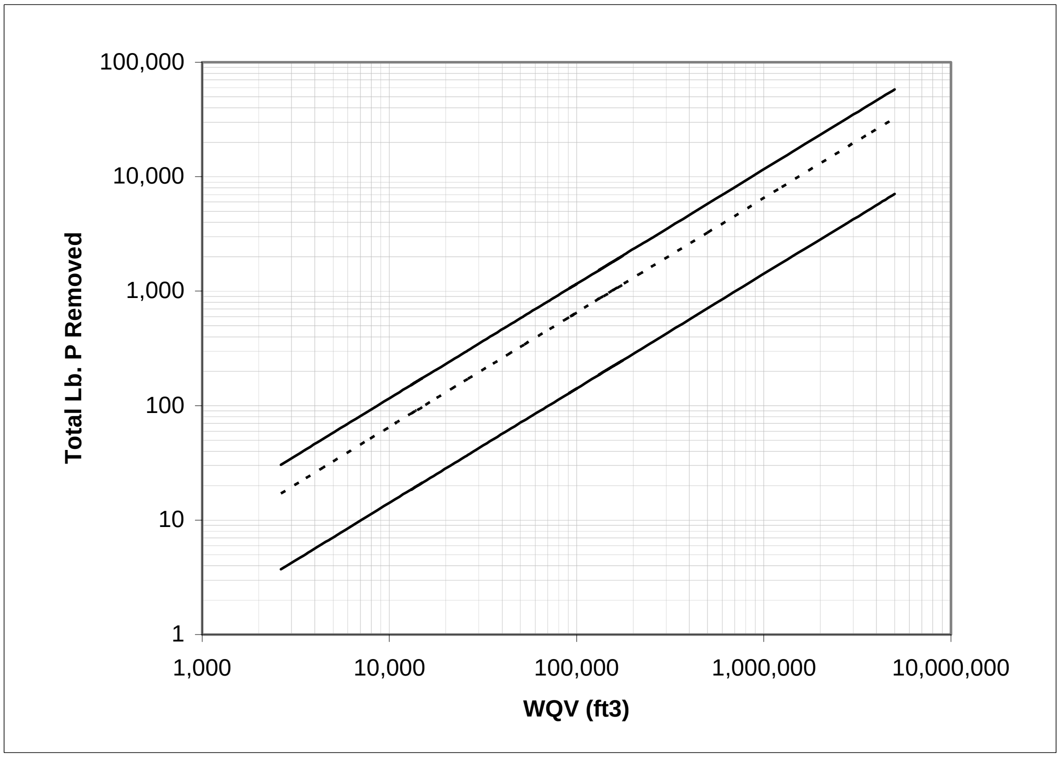

Figure 34. Estimated P removed in 20 years for wet basins with the 67% CI.

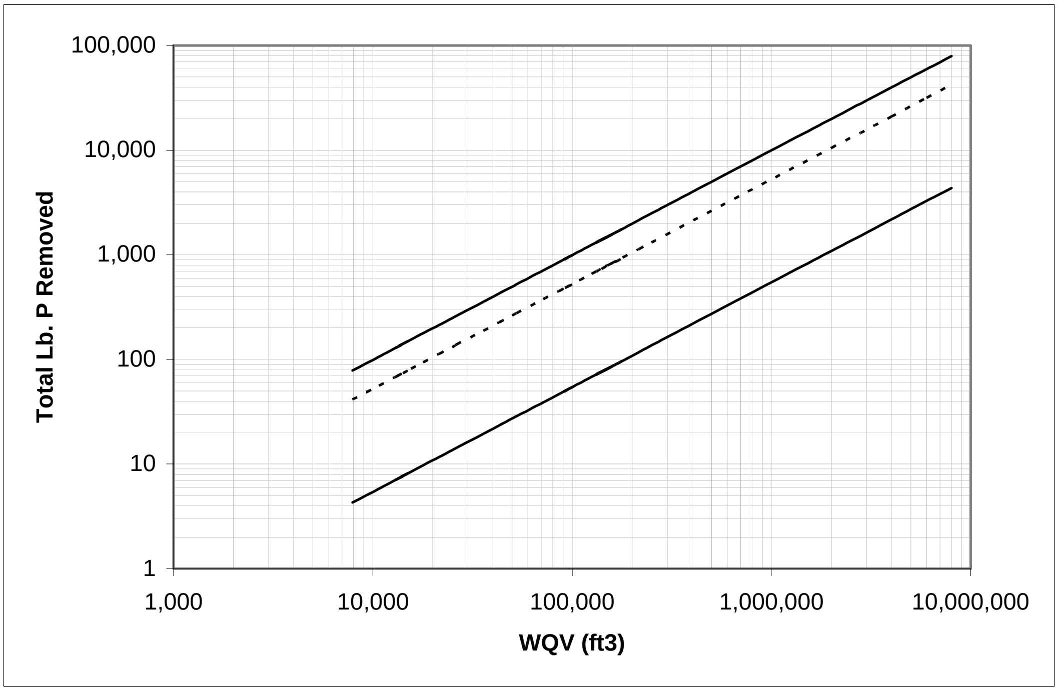

Figure 35. Estimated P removed in 20 years for constructed wetlands with the 67% CI.

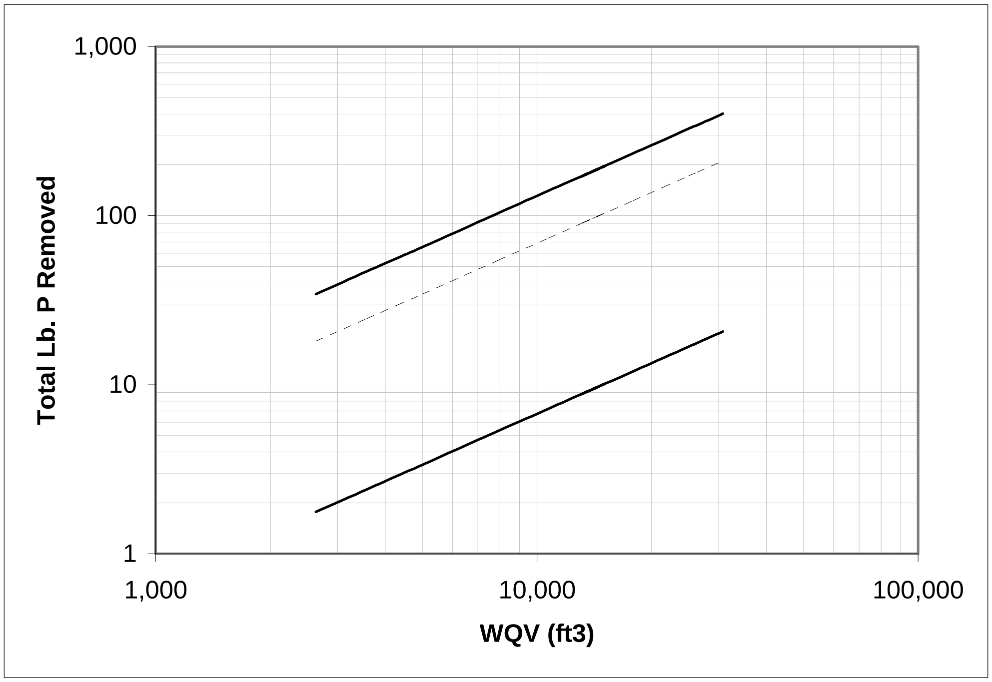

Figure 36. Estimated P removed in 20 years for infiltration trenches with the 67% CI.

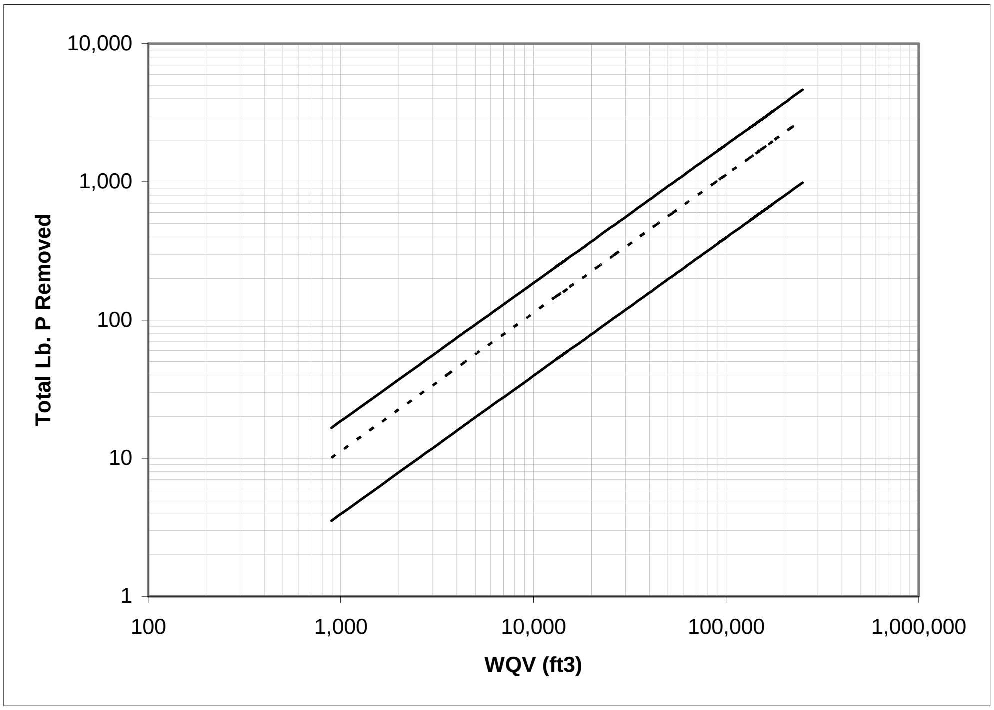

Figure 37. Estimated P removed in 20 years for bioinfiltration filters with the 67% CI.

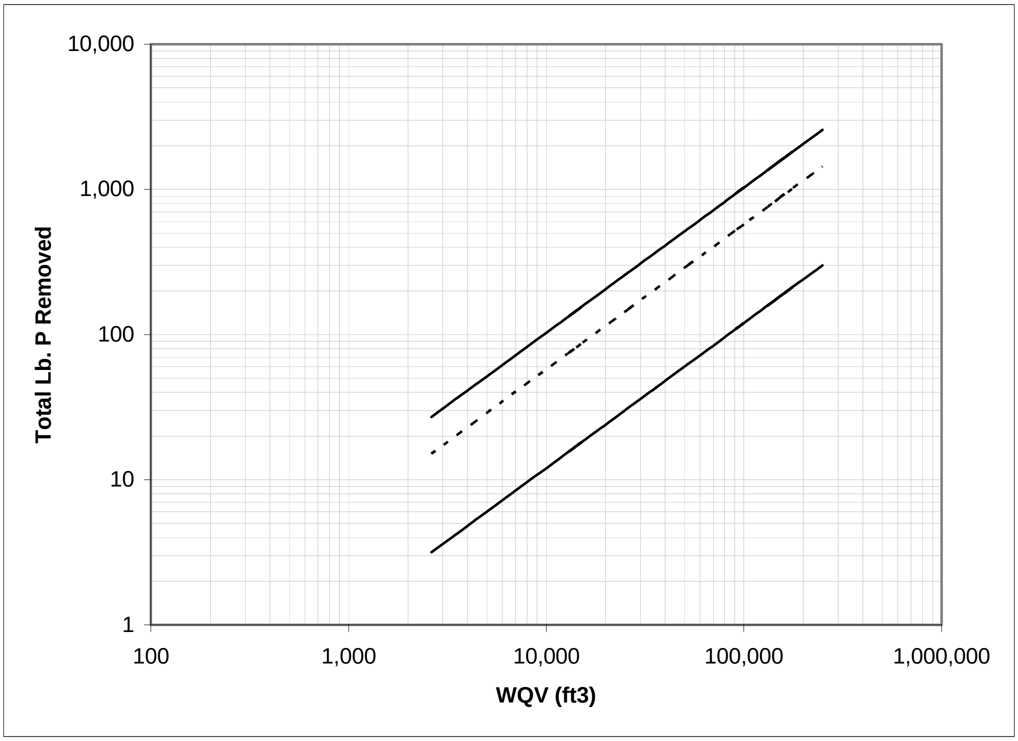

Figure 38. Estimated P removed in 20 years for sand filters with the 67% CI.

Examples

SMPs under consideration for a 50-acre watershed that is 80 percent impervious include a dry detention basin and a constructed wetland. The SMP is to be designed for a 1.45-inch precipitation depth and a comparison of the cost and effectiveness of both SMPs is desired.

Using Equations 1 and 2, the WQV can be determined as follows:

$$\begin{aligned}\mathrm{WQV} &= \left(\frac{43560}{12}\right) * 1.45 * \left(0.05 + 0.009(80)\right) * 50 \\ \mathrm{WQV} &\approx 200{,}000\ \mathrm{ft}^3\end{aligned}$$

From Figure 19, the TPC of an average dry detention basin of this size is just over \$300,000 with a 67% confidence interval range of about \$170,000 to \$675,000. A similarly sized average wetland would, based on Figure 21, cost approximately \$200,000 with a 67% confidence interval range of \$110,000 to \$400,000. For a comparison among all SMPs, Table 9 lists the estimated average TPC of all practices analyzed herein for various WQVs. For each SMP, TPCs are not estimated for WQVs that are outside the range of the original construction cost data. Thus some values in Table 9 do not have a cost entry.

Investigation of Table 9 reveals that, based on the collected data and in terms of TPC, wetlands are the least expensive SMP for the range of WQVs listed. This finding is somewhat similar to that of Wossink and Hunt (2003) who concluded that, in terms of construction costs, wetlands were the least expensive of four SMPs (wet ponds, constructed wetlands, sand filters, bioretention basins) for watersheds larger than 10 acres in sandy soils. Contrary to the previous conclusions, the California Stormwater Quality Association (2003) states that wetlands are relatively inexpensive but are typically 25% more expensive than stormwater ponds of equivalent volume. One must also remember that since wetlands generally require more land area, any savings in TPC may potentially be more than offset by larger land acquisition costs.

Over 20 years the estimated TSS removal and 67% confidence interval for the dry detention basin can, with the use of Figure 27, be estimated to be 344,000 pounds with a range of 120,000 pounds to 570,000 pounds. The corresponding wetland TSS removal based on Figure 29 is estimated to be 440,000 pounds with a range of 210,000 pounds to 673,000 pounds.

The phosphorus removed over 20 years can be estimated in a similar manner using Figures 33 and 35. For the dry detention basin the average P removal is approximately 630 pounds with a range of 80 to 1,200 pounds (67% confidence interval). The wetland average P removal is about 1,050 pounds with a range from about 110 pounds to about 2,000 pounds. Thus, for this watershed and design depth, the wetland, on average, would cost less to construct (not including land costs) and it would also remove more TSS and phosphorus. However, land costs must always be considered.

Focusing on associated land costs of each SMP under consideration, Table 3 can be used to estimate the range of expected land area required for each SMP. Using the values based on total watershed area and selecting the high end of each range, the dry detention basin would require 2.0 percent of the total watershed area resulting in a basin land area of 1 acre. Similarly, the wetland would require 5.0 percent of 50 acres or 2.5 acres. If land costs are known, the land areas can be used to estimate land costs associated with each SMP. For example, if land costs were $10,000 per acre, acquiring the land for the detention basin would cost an additional $10,000 and the land for the wetland would cost $25,000. The resulting total cost (now including a rough estimate for land acquisition) for the detention basin and wetland would be $310,000 and $225,000, respectively. Thus, in this relatively low land-cost scenario, the wetland would still be cheaper and more effective, on average. However, if land costs in the vicinity of the project were $250,000 per acre, an average dry detention basin would, including land, have an estimated total cost of \$550,000 and the wetland under consideration would have a total cost of \$825,000. Thus, with more expensive land, wetlands are no longer the less expensive option.

	Water Quality Volume (ft^3)				
SMP	**3,000**	**10,000**	**30,000**	**100,000**	**250,000**
Dry Det. Basin	22	46	91	198	359
Wet/Ret. Basin	47	83	141	256	407
Const. Wetland	21	38	68	131	219
Infilt. Trench	84	226	554	--	--
Bioinfilt. Filter	49	122	286	--	--
Sand Filter	86	176	338	691	--

Table 9. Average Total Present Cost (in \$1,000) of SMPs at varying WQVs. Land costs are excluded, and need to be determined separately.

However, wetlands are still estimated to remove more TSS and phosphorus, meaning that the parties involved would have to weigh the increased cost of the wetland against its added benefit (*i.e.* more contaminant removal). This example and the intended use for this report are preliminary in nature; to obtain a more accurate estimate of costs a more detailed design of each SMP should be completed.

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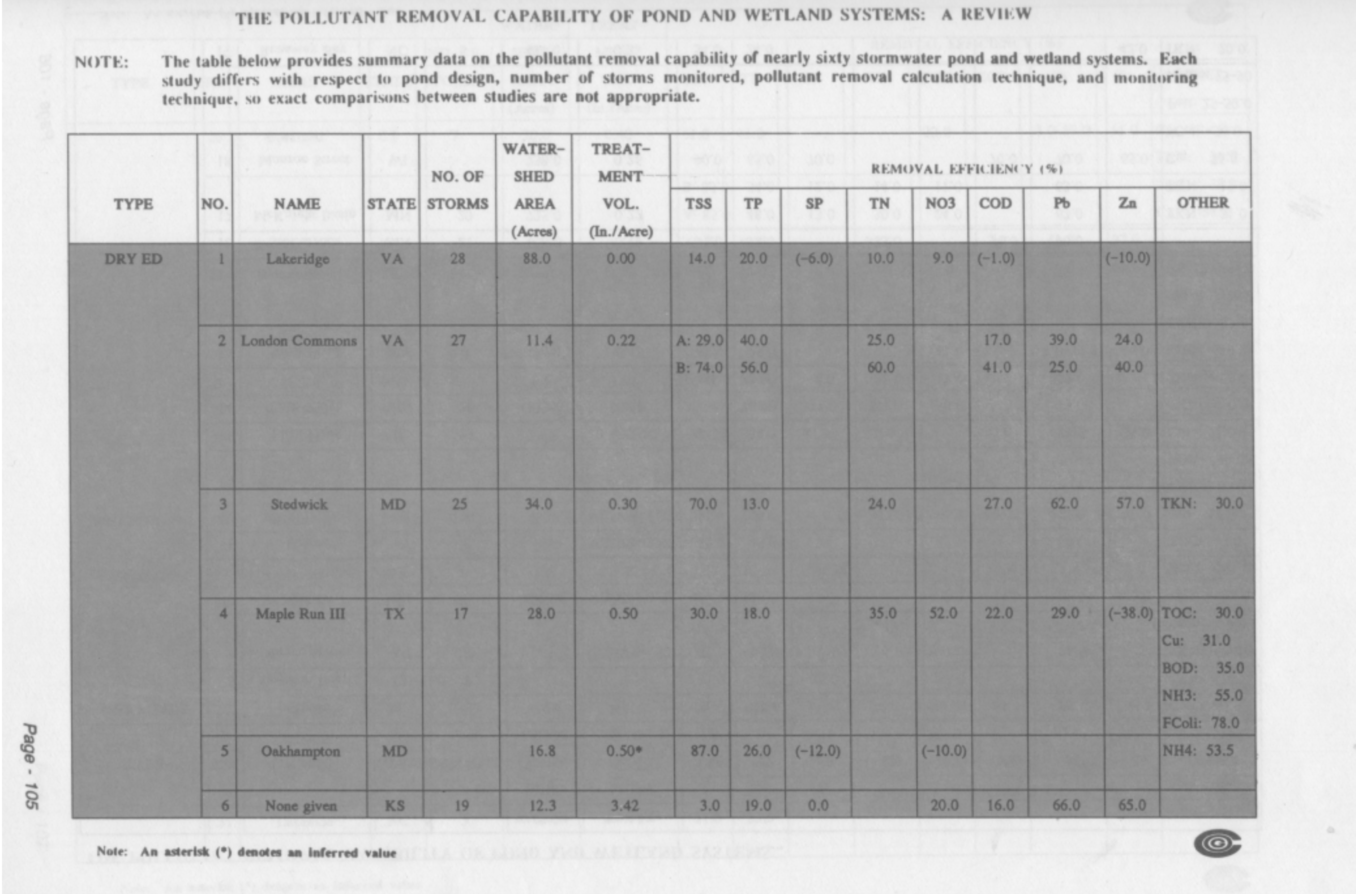
Appendix A - Pollutant Removal Capability Table: References, Notes and Notation



THE POLLUTANT REMOVAL CAPABILITY OF POND AND WETLAND SYSTEMS: A REVIEW

NOTE: The table below provides summary data on the pollutant removal capability of nearly sixty stormwater pond and wetland systems. Each study differs with respect to pond design, number of storms monitored, pollutant removal calculation technique, and monitoring technique, so exact comparisons between studies are not appropriate.

TYPE	NO.	NAME	STATE	NO. OF STORMS	WATER-SHED AREA (Acres)	TREAT-MENT VOL. (In./Acre)	REMOVAL EFFICIENCY (%) TSS	TP	SP	TN	NO3	COD	Pb	Zn	OTHER
DRY ED	1	Lakeridge	VA	28	88.0	0.00	14.0	20.0	(-6.0)	10.0	9.0	(-1.0)		(-10.0)	
	2	London Commons	VA	27	11.4	0.22	A: 29.0 B: 74.0	40.0 56.0		25.0 60.0		17.0 41.0	39.0 25.0	24.0 40.0	
	3	Stedwick	MD	25	34.0	0.30	70.0	13.0		24.0		27.0	62.0	57.0	TKN: 30.0
	4	Maple Run III	TX	17	28.0	0.50	30.0	18.0		35.0	52.0	22.0	29.0	(-38.0)	TOC: 30.0 Cu: 31.0 BOD: 35.0 NH3: 55.0 FColi: 78.0
	5	Oakhampton	MD		16.8	0.50*	87.0	26.0	(-12.0)		(-10.0)				NH4: 53.5
	6	None given	KS	19	12.3	3.42	3.0	19.0	0.0		20.0	16.0	66.0	65.0	

Note: An asterisk (*) denotes an inferred value

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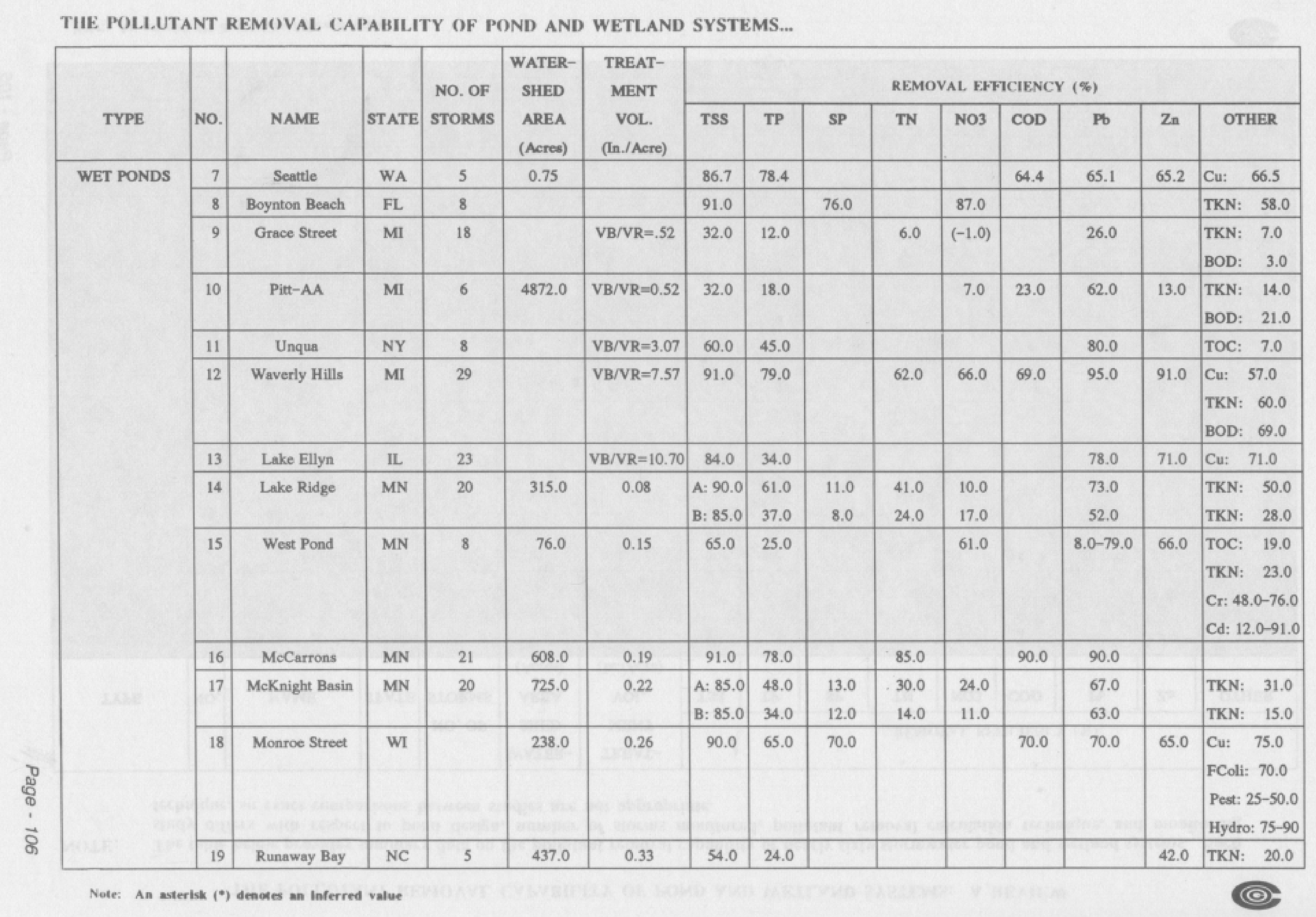
Note: DRY ED stands for Dry Extended Detention. Extended detention systems, as referred to in the above table are synonymous with dry detention basins, and are designed to release all runoff influent within a 24 hour period.



THE POLLUTANT REMOVAL CAPABILITY OF POND AND WETLAND SYSTEMS...

TYPE	NO.	NAME	STATE	NO. OF STORMS	WATER-SHED AREA (Acres)	TREAT-MENT VOL. (In./Acre)	REMOVAL EFFICIENCY (%) TSS	TP	SP	TN	NO3	COD	Pb	Zn	OTHER
WET PONDS	7	Seattle	WA	5	0.75		86.7	78.4				64.4	65.1	65.2	Cu: 66.5
	8	Boynton Beach	FL	8			91.0		76.0		87.0				TKN: 58.0
	9	Grace Street	MI	18		VB/VR=.52	32.0	12.0		6.0	(−1.0)		26.0		TKN: 7.0 BOD: 3.0
	10	Pitt–AA	MI	6	4872.0	VB/VR=0.52	32.0	18.0			7.0	23.0	62.0	13.0	TKN: 14.0 BOD: 21.0
	11	Unqua	NY	8		VB/VR=3.07	60.0	45.0					80.0		TOC: 7.0
	12	Waverly Hills	MI	29		VB/VR=7.57	91.0	79.0		62.0	66.0	69.0	95.0	91.0	Cu: 57.0 TKN: 60.0 BOD: 69.0
	13	Lake Ellyn	IL	23		VB/VR=10.70	84.0	34.0					78.0	71.0	Cu: 71.0
	14	Lake Ridge	MN	20	315.0	0.08	A: 90.0	61.0	11.0	41.0	10.0		73.0		TKN: 50.0
							B: 85.0	37.0	8.0	24.0	17.0		52.0		TKN: 28.0
	15	West Pond	MN	8	76.0	0.15	65.0	25.0			61.0		8.0–79.0	66.0	TOC: 19.0 TKN: 23.0 Cr: 48.0–76.0 Cd: 12.0–91.0
	16	McCarrons	MN	21	608.0	0.19	91.0	78.0		85.0		90.0	90.0		
	17	McKnight Basin	MN	20	725.0	0.22	A: 85.0	48.0	13.0	30.0	24.0		67.0		TKN: 31.0
							B: 85.0	34.0	12.0	14.0	11.0		63.0		TKN: 15.0
	18	Monroe Street	WI		238.0	0.26	90.0	65.0	70.0			70.0	70.0	65.0	Cu: 75.0 FColi: 70.0 Pest: 25–50.0 Hydro: 75–90
	19	Runaway Bay	NC	5	437.0	0.33	54.0	24.0						42.0	TKN: 20.0

Note: An asterisk (*) denotes an inferred value

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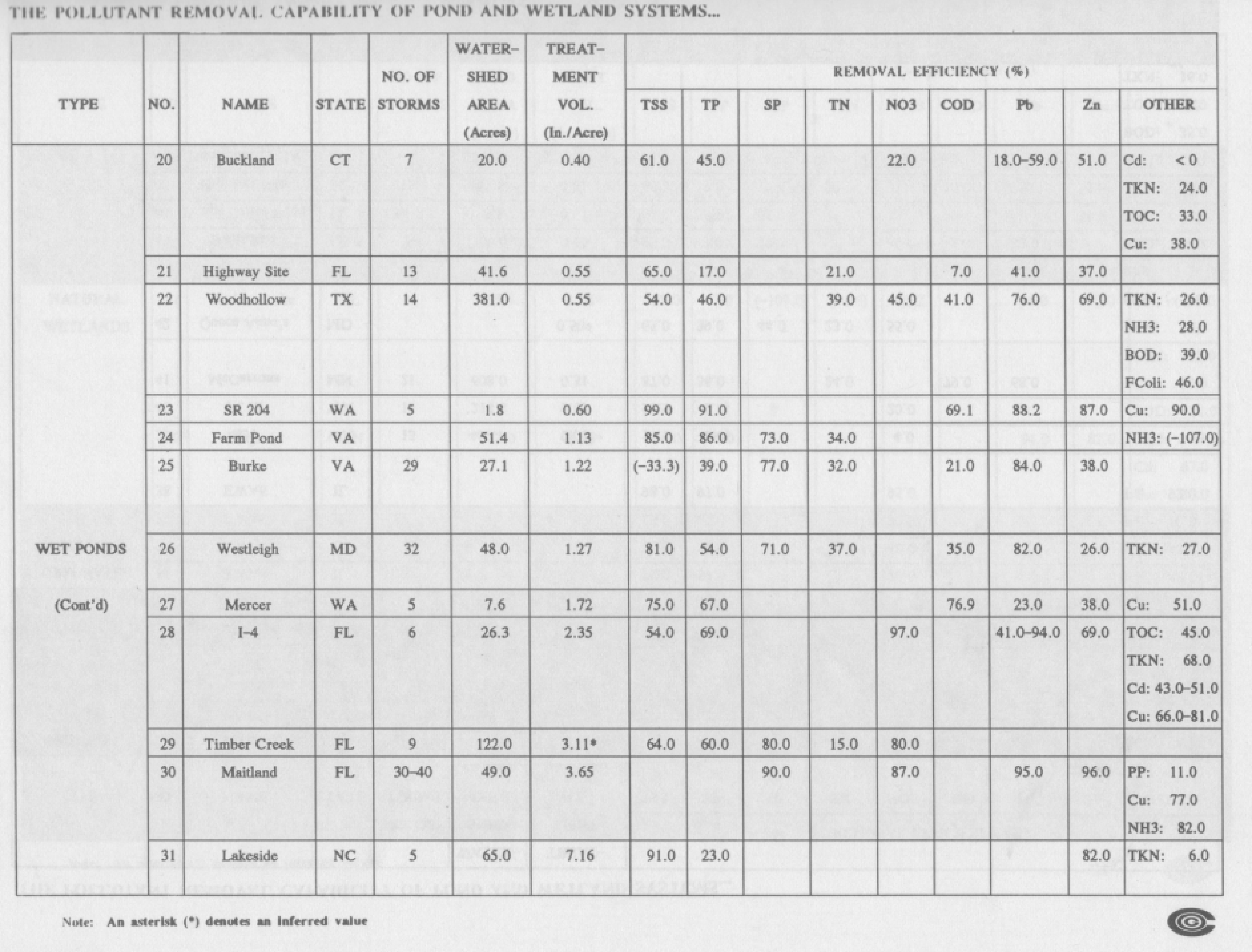
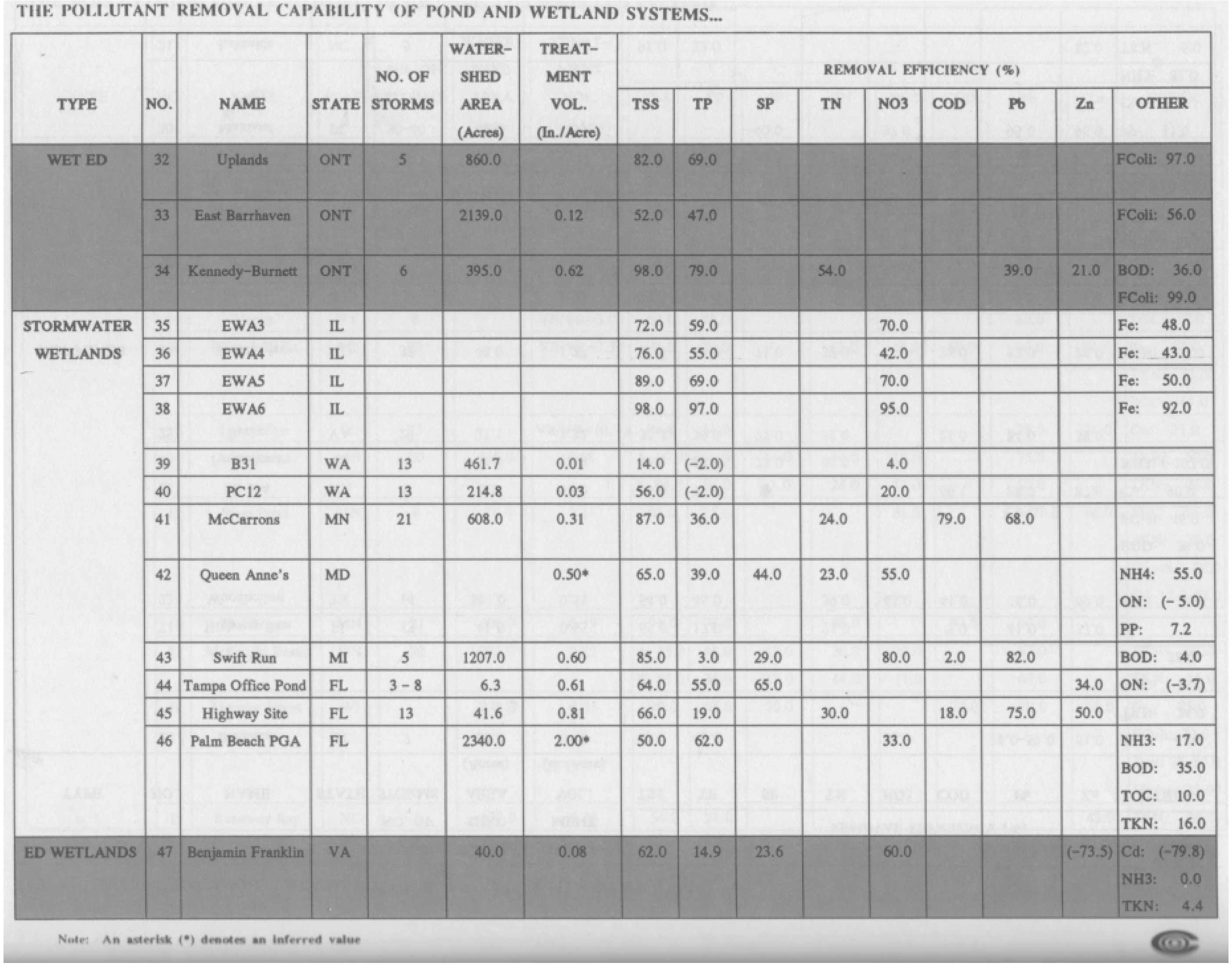


THE POLLUTANT REMOVAL CAPABILITY OF POND AND WETLAND SYSTEMS...

TYPE	NO.	NAME	STATE	NO. OF STORMS	WATER-SHED AREA (Acres)	TREAT-MENT VOL. (In./Acre)	REMOVAL EFFICIENCY (%) TSS	TP	SP	TN	NO3	COD	Pb	Zn	OTHER
WET PONDS (Cont'd)	20	Buckland	CT	7	20.0	0.40	61.0	45.0			22.0		18.0–59.0	51.0	Cd: < 0 TKN: 24.0 TOC: 33.0 Cu: 38.0
	21	Highway Site	FL	13	41.6	0.55	65.0	17.0		21.0		7.0	41.0	37.0	
	22	Woodhollow	TX	14	381.0	0.55	54.0	46.0		39.0	45.0	41.0	76.0	69.0	TKN: 26.0 NH3: 28.0 BOD: 39.0 FColi: 46.0
	23	SR 204	WA	5	1.8	0.60	99.0	91.0				69.1	88.2	87.0	Cu: 90.0
	24	Farm Pond	VA		51.4	1.13	85.0	86.0	73.0	34.0					NH3: (−107.0)
	25	Burke	VA	29	27.1	1.22	(−33.3)	39.0	77.0	32.0		21.0	84.0	38.0	
	26	Westleigh	MD	32	48.0	1.27	81.0	54.0	71.0	37.0		35.0	82.0	26.0	TKN: 27.0
	27	Mercer	WA	5	7.6	1.72	75.0	67.0				76.9	23.0	38.0	Cu: 51.0
	28	I-4	FL	6	26.3	2.35	54.0	69.0			97.0		41.0–94.0	69.0	TOC: 45.0 TKN: 68.0 Cd: 43.0–51.0 Cu: 66.0–81.0
	29	Timber Creek	FL	9	122.0	3.11*	64.0	60.0	80.0	15.0	80.0				
	30	Maitland	FL	30–40	49.0	3.65			90.0		87.0		95.0	96.0	PP: 11.0 Cu: 77.0 NH3: 82.0
	31	Lakeside	NC	5	65.0	7.16	91.0	23.0						82.0	TKN: 6.0

Note: An asterisk (*) denotes an inferred value

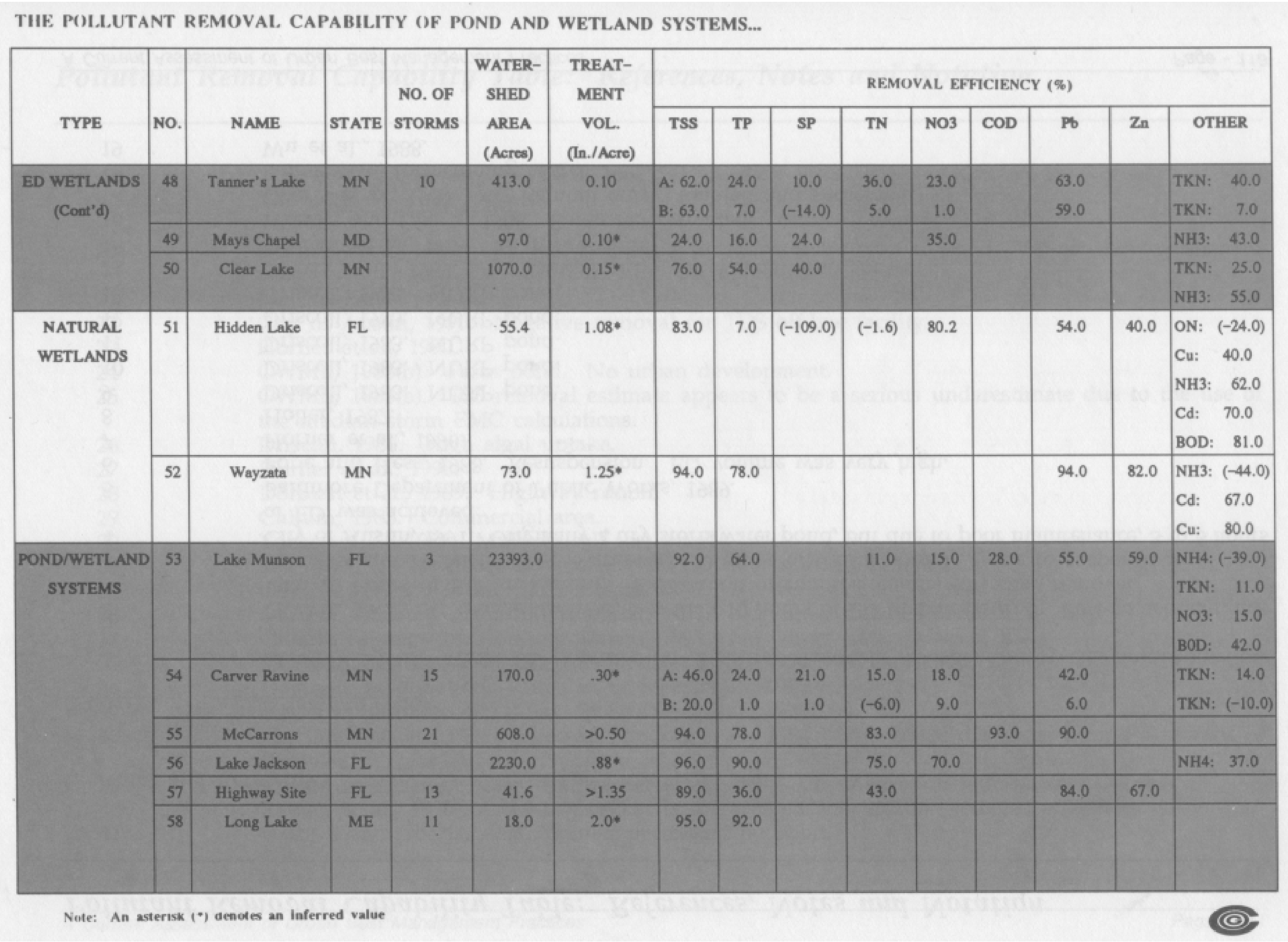


THE POLLUTANT REMOVAL CAPABILITY OF POND AND WETLAND SYSTEMS...

TYPE	NO.	NAME	STATE	NO. OF STORMS	WATER-SHED AREA (Acres)	TREAT-MENT VOL. (In./Acre)	REMOVAL EFFICIENCY (%)								
							TSS	TP	SP	TN	NO3	COD	Pb	Zn	OTHER
WET ED	32	Uplands	ONT	5	860.0		82.0	69.0							FColi: 97.0
	33	East Barrhaven	ONT		2139.0	0.12	52.0	47.0							FColi: 56.0
	34	Kennedy-Burnett	ONT	6	395.0	0.62	98.0	79.0		54.0			39.0	21.0	BOD: 36.0 FColi: 99.0
STORMWATER WETLANDS	35	EWA3	IL				72.0	59.0			70.0				Fe: 48.0
	36	EWA4	IL				76.0	55.0			42.0				Fe: 43.0
	37	EWA5	IL				89.0	69.0			70.0				Fe: 50.0
	38	EWA6	IL				98.0	97.0			95.0				Fe: 92.0
	39	B31	WA	13	461.7	0.01	14.0	(-2.0)			4.0				
	40	PC12	WA	13	214.8	0.03	56.0	(-2.0)			20.0				
	41	McCarrons	MN	21	608.0	0.31	87.0	36.0		24.0		79.0	68.0		
	42	Queen Anne's	MD			0.50*	65.0	39.0	44.0	23.0	55.0				NH4: 55.0 ON: (- 5.0) PP: 7.2
	43	Swift Run	MI	5	1207.0	0.60	85.0	3.0	29.0		80.0	2.0	82.0		BOD: 4.0
	44	Tampa Office Pond	FL	3 - 8	6.3	0.61	64.0	55.0	65.0					34.0	ON: (-3.7)
	45	Highway Site	FL	13	41.6	0.81	66.0	19.0		30.0		18.0	75.0	50.0	
	46	Palm Beach PGA	FL		2340.0	2.00*	50.0	62.0			33.0				NH3: 17.0 BOD: 35.0 TOC: 10.0 TKN: 16.0
ED WETLANDS	47	Benjamin Franklin	VA		40.0	0.08	62.0	14.9	23.6		60.0			(-73.5)	Cd: (-79.8) NH3: 0.0 TKN: 4.4

Note: An asterisk (*) denotes an inferred value

Note: WET ED stands for Wet Extended Detention. Extended detention systems, as referred to in the above table are synonymous with retention basins, and are designed to store runoff until a runoff event displaces the amount of water stored.



THE POLLUTANT REMOVAL CAPABILITY OF POND AND WETLAND SYSTEMS...

TYPE	NO.	NAME	STATE	NO. OF STORMS	WATERSHED AREA (Acres)	TREATMENT VOL. (In./Acre)	REMOVAL EFFICIENCY (%)								
							TSS	TP	SP	TN	NO3	COD	Pb	Zn	OTHER
ED WETLANDS (Cont'd)	48	Tanner's Lake	MN	10	413.0	0.10	A: 62.0 B: 63.0	24.0 7.0	10.0 (−14.0)	36.0 5.0	23.0 1.0		63.0 59.0		TKN: 40.0 TKN: 7.0
	49	Mays Chapel	MD		97.0	0.10*	24.0	16.0	24.0		35.0				NH3: 43.0
	50	Clear Lake	MN		1070.0	0.15*	76.0	54.0	40.0						TKN: 25.0 NH3: 55.0
NATURAL WETLANDS	51	Hidden Lake	FL		55.4	1.08*	83.0	7.0	(−109.0)	(−1.6)	80.2		54.0	40.0	ON: (−24.0) Cu: 40.0 NH3: 62.0 Cd: 70.0 BOD: 81.0
	52	Wayzata	MN		73.0	1.25*	94.0	78.0					94.0	82.0	NH3: (−44.0) Cd: 67.0 Cu: 80.0
POND/WETLAND SYSTEMS	53	Lake Munson	FL	3	23393.0		92.0	64.0		11.0	15.0	28.0	55.0	59.0	NH4: (−39.0) TKN: 11.0 NO3: 15.0 BOD: 42.0
	54	Carver Ravine	MN	15	170.0	.30*	A: 46.0 B: 20.0	24.0 1.0	21.0 1.0	15.0 (−6.0)	18.0 9.0		42.0 6.0		TKN: 14.0 TKN: (−10.0)
	55	McCarrons	MN	21	608.0	>0.50	94.0	78.0		83.0		93.0	90.0		
	56	Lake Jackson	FL		2230.0	.88*	96.0	90.0		75.0	70.0				NH4: 37.0
	57	Highway Site	FL	13	41.6	>1.35	89.0	36.0		43.0			84.0	67.0	
	58	Long Lake	ME	11	18.0	2.0*	95.0	92.0							

Note: An asterisk (*) denotes an inferred value

Note: ED Wetlands stand for Extended Detention Wetlands. Extended detention systems, as referred to in the above table are similar to wetlands, but may store stormwater runoff for a longer period than typical wetland systems. Natural Wetlands refers to systems that have been modified or utilized for stormwater treatment from natural wetlands, as opposed to constructed systems.

Appendix B – Data used to estimate average SMP effectiveness

Appendix B1 – Dry Detention Ponds

Dry Detention Ponds								
Source	**ID**	**Inflow [TSS}**	**Outflow [TSS]**	**Inflow [P]**	**Outflow [P]**	**% TSS removed**	**% P removed**	**Comment**
Winer, Nat'l Poll. Rem. Database, 2000	#1	77	10	0.188	0.112	87	40	Conc. Basis
Winer, Nat'l Poll. Rem. Database, 2000	#3	68	38	0.21	0.18	44	14	"
Winer, Nat'l Poll. Rem. Database, 2000	#6	98	28	0.35	0.27	71	23	"
Winer, Nat'l Poll. Rem. Database, 2000	#6	--	--	--	--	71	14	"
Caltrans 2004 BMP Retrofit Pilot Program Final Report, App F	I5/605 Int	--	--	--	--	5	-4	"
Caltrans 2004 BMP Retrofit Pilot Program Final Report, App F	Manchester	--	--	--	--	70	42	"
Caltrans 2004 BMP Retrofit Pilot Program Final Report, App F	SR56/I5	--	--	--	--	43	21	"
Caltrans 2004 BMP Retrofit Pilot Program Final Report, App F	SR78/I5	--	--	--	--	55	33	"
Environ & Conservation Services Dept. Austin TX. Removal Efficiencies of Stormwater Control Structures. May 1990.	Maple Run III	--	--	--	--	30	18	Mass Basis
Commings, Booth, & Horner, 2000. Stormwater Pollutant Removal in two wet ponds in Bellevue, WA. Jour. Environ. Engrg, 126(4):321-330	--	--	--	--	--	61.60	20.00	"
Stanley, 1996. Pollutant Removal by a stormwater dry detention pond. Water Environ. Research, 68(6):1076-1083.	--	127	32	0.41	0.3	75	27	Conc. Basis
Harper. Pollutant Removal Efficiences for Typical Stormwater Management Systems in Florida.	--	--	--	--	--	85	61	"
BMP Database. Greenville Pond, Greenville, NC	--	--	--	--	--	--	27	"

Dry Extended Detention Pond (cont'd)

Source	ID	Inflow [TSS}	Outflow [TSS]	Inflow [P]	Outflow [P]	% TSS removed	% P removed	Comment
Metropoliton Washington Council of Governments, 1992. A Current Assessment of Urban Best Management Practices-Techniques for Reducing Non-Point Source Pollution in the Coastal Zone.	Lakeridge, VA	--	--	--	--	14	20	unknown basis
Metropoliton Washington Council of Governments, 1992. A Current Assessment of Urban Best Management Practices-Techniques for Reducing Non-Point Source Pollution in the Coastal Zone.	London Commons, VA	--	--	--	--	52	48	unknown basis
Metropoliton Washington Council of Governments, 1992. A Current Assessment of Urban Best Management Practices-Techniques for Reducing Non-Point Source Pollution in the Coastal Zone.	Stedwick, MD	--	--	--	--	70	13	unknown basis
Metropoliton Washington Council of Governments, 1992. A Current Assessment of Urban Best Management Practices-Techniques for Reducing Non-Point Source Pollution in the Coastal Zone.	Oakhampton, MD	--	--	--	--	30	18	unknown basis
Metropoliton Washington Council of Governments, 1992. A Current Assessment of Urban Best Management Practices-Techniques for Reducing Non-Point Source Pollution in the Coastal Zone.	Unknown	--	--	--	--	87	26	unknown basis
Pope, L..M. and L.G. Hess, Date unknown. "Load Detention Efficiencies in a Dry-Pond Basin," from Kansas State Library.	Topeka, KS	--	--	--	--	3	19	Mass Basis

Appendix B2 – Wet Basins

Wet Basins								
Source	**ID**	**Inflow [TSS}**	**Outflow [TSS]**	**Inflow [P]**	**Outflow [P]**	**% TSS removed**	**% P removed**	**Comment**
Metropoliton Washington Council of Governments, 1992. A Current Assessment of Urban Best Management Practices-Techniques for Reducing Non-Point Source Pollution in the Coastal Zone.	Uplands, Ont	--	--	--	--	82	69	Unknown Basis
"	E. Barrhaven, Ont	--	--	--	--	52	47	"
"	Kennedy-Burnett, Ont	--	--	--	--	98	79	"
Winer, Nat'l Poll. Rem. Database, 2000	#11	177	39	0.761	0.214	78	72	Concentration Basis
"	#11	--	--	--	--	60	46	Mass Basis
"	#13	61	49	0.162	0.103	20	36	Concentration Basis
"	#13	--	--	--	--	20	37	Mass Basis
"	#14	16.2	2.9	0.087	0.045	82	48	Concentration Basis
"	#15	--	--	--	--	87	79	Mass Basis
"	#16	--	--	--	--	80.00	37.00	Concentration Basis
"	#17	--	--	0.88	0.13		85	Concentration Basis
"	#18	71	12	0.232	0.112	83	52	Concentration Basis
"	#22	45	14	0.651	0.164	69	75	Concentration Basis

Wet Basins (cont'd)								
Source	**ID**	**Inflow [TSS}**	**Outflow [TSS]**	**Inflow [P]**	**Outflow [P]**	**% TSS removed**	**% P removed**	**Comment**
Winer, Nat'l Poll. Rem. Database, 2000	#22	--	--	--	--	67	57	Mass Basis
"	#23	28	11	0.4	0.176	61	56	Concentration Basis
"	#23	--	--	--	--	71	62	Mass Basis
"	#24	131	7	0.497	0.053	95	89	Concentration Basis
"	#24	--	--	--	--	94	90	Mass Basis
"	#26	128	9	0.3	0.04	93	87	Concentration Basis
"	#27	22.8	8.9	0.095	0.077	61	19	Concentration Basis
"	#28	20.6	6.5	0.136	0.035	68	74	Concentration Basis
"	#29	7	15	0.272	0.155	-114	43	Concentration Basis

Wet Basins (cont'd)								
Source	**ID**	**Inflow [TSS}**	**Outflow [TSS]**	**Inflow [P]**	**Outflow [P]**	**% TSS removed**	**% P removed**	**Comment**
Winer, Nat'l Poll. Rem. Database, 2000	#29	--	--	--	--	54	69	Mass Basis
"	#30	52	23	0.3	0.4	56	-33	Concentration Basis
"	#30	--	--	--	--	65	25	Mass Basis
"	#31	47	54	0.247	0.195	-15	21	Concentration Basis
"	#31	--	--	--	--	61	45	Mass Basis
"	#38	45	19	0.17	0.12	58	29	Concentration Basis
"	#42	--	--	--	--	7	40	Concentration Basis
"	#43	--	--	--	--	80.00	80.00	Mass Basis
"	#44	--	--	--	--	75.00	22.00	Concentration Basis
"	#44	--	--	--	--	83.00	37.00	Mass Basis
"	#45	1113	63	2.91	0.27	94.34	90.72	Concentration Basis
"	#45	--	--	--	--	93.00	79.00	Mass Basis
"	#47	--	--	--	--	85.00	48.00	Mass Basis

Wet Basins (cont'd)								
Source	**ID**	**Inflow [TSS}**	**Outflow [TSS]**	**Inflow [P]**	**Outflow [P]**	**% TSS removed**	**% P removed**	**Comment**
Winer, Nat'l Poll. Rem. Database, 2000	#50	134	28	0.45	0.21	79.10	53.33	Concentration Basis
"	#51	--	--	0.12	0.08	--	33	Concentration Basis
"	#52	--	--	0.14	0.08	--	43	Concentration Basis
"	#52	--	--	--	--	93	45	Mass Basis
Environ & Conservation Services Dept. Austin TX. Removal Efficiencies of Stormwater Control Structures. May 1990.	Wood-hollow	--	--	--	--	54	46	Mass Basis
Cazanacli, 2003. Comparing Sediment Removal Rates of Manufactured BMPs to Wet Basins. Water Resources Conf. Oct. 28, 2003. Brooklyn Park, MN		--	--	--	--	70	--	Mass Basis
Commings, Booth, & Horner, 2000. Stormwater Pollutant Removal in two wet ponds in Bellevue, WA. Jour. Environ. Engrg, 126(4):321-330		--	--	--	--	81	--	Mass Basis
Mallin, Ensign, Wheeler, Mayes, 2002. Surface Water Quality-Pollutant Removal Efficacy of Three Wet Detention Ponds. Jour. Environ Quality 31:654-660.	Ann McCrary	10.5	3.7	0.061	0.047	65	23	Concentration Basis
Oberts, 1994. Performance of Stormwater Ponds and Wetlands in Winter. In "Watershed Protection Techniques," Vol 1(2), Center for Watershed Protection. (Data for 4 wet ponds receiving rainfall)		--	--	--	--	78	53	Rainfall Event. Appears to be Concentration Basis
Oberts, 1994. Performance of Stormwater Ponds and Wetlands in Winter. In "Watershed Protection Techniques," Vol 1(2), Center for Watershed Protection. (Data for 4 wet ponds receiving snowmelt)		--	--	--	--	39	16	Snowmelt Event. Appears to be Concentration Basis
Harper. Pollutant Removal Efficiences for Typical Stormwater Management Systems in Florida.		--	--	--	--	76	29	Mass Basis
Harper. Pollutant Removal Efficiences for Typical Stormwater Management Systems in Florida.		--	--	--	--	93	73	Mass Basis
Harper. Pollutant Removal Efficiences for Typical Stormwater Management Systems in Florida.		--	--	--	--	94	69	Concentration Basis

Wet Basins (cont'd)								
Source	**ID**	**Inflow [TSS}**	**Outflow [TSS]**	**Inflow [P]**	**Outflow [P]**	**% TSS removed**	**% P removed**	**Comment**
Harper. Pollutant Removal Efficiences for Typical Stormwater Management Systems in Florida.	--	--	--	--	--	68	55	Concentration Basis
Harper. Pollutant Removal Efficiences for Typical Stormwater Management Systems in Florida.	--	--	--	--	--	64	60	Mass Basis
Harper. Pollutant Removal Efficiences for Typical Stormwater Management Systems in Florida.	--	--	--	--	--	--	81	Concentration Basis
Harper. Pollutant Removal Efficiences for Typical Stormwater Management Systems in Florida.	--	--	--	--	--	--	62	Concentration Basis
Harper. Pollutant Removal Efficiences for Typical Stormwater Management Systems in Florida.	--	--	--	--	--	66	38	Concentration Basis
Harper. Pollutant Removal Efficiences for Typical Stormwater Management Systems in Florida.	--	--	--	--	--	82	91	Mass Basis
Harper. Pollutant Removal Efficiences for Typical Stormwater Management Systems in Florida.	--	--	--	--	--	85	60	Mass Basis
Harper. Pollutant Removal Efficiences for Typical Stormwater Management Systems in Florida.	--	--	--	--	--	85	70	Mass Basis
Harper. Pollutant Removal Efficiences for Typical Stormwater Management Systems in Florida.	--	--	--	--	--	55	65	Mass Basis
Wu, J.S., R.E. Holman, and J.R. Dorney, 1996. Systematic Evaluation of Pollutant Removal by Urban Wet Detention Ponds. (Lake Side Pond)	--	--	--	--	--	93	45	Concentration Basis
Wu, J.S., R.E. Holman, and J.R. Dorney, 1996. Systematic Evaluation of Pollutant Removal by Urban Wet Detention Ponds. (Waterford Pond)	--	--	--	--	--	41	--	Concentration Basis
Wu, J.S., R.E. Holman, and J.R. Dorney, 1996. Systematic Evaluation of Pollutant Removal by Urban Wet Detention Ponds. (Runaway Bay Pond)	--	--	--	--	--	62	36	Concentration Basis
BMP Database. Site: Lake Ridge Det. Pond, Woodbury, MN	--	--	--	--	--		58	Concentration Basis

Wet Basins (cont'd)									
Source	**ID**	**Inflow [TSS}**	**Outflow [TSS]**	**Inflow [P]**	**Outflow [P]**	**% TSS removed**	**% P removed**	**Comment**
BMP Database. Site: Lakeside Pond, Charlotte, NC.	--	--	--	--	--	--	44	Concentration Basis
	--	--	--	--	--	--		Concentration Basis
BMP Database. Site: Pittsfield Ret. Pond, Ann Arbor, MI	--	--	--	--	--	--	15	Concentration Basis
BMP Database. Site: Tampa Office Pond, Tampa, FL	--	--	--	--	--	--	77	Concentration Basis
BMP Database. Site: Traver Creek Ret. Pond, Ann Arbor, MI	--	--	--	--	--	--	40	Concentration Basis
Metropoliton Washington Council of Governments, 1992. A Current Assessment of Urban Best Management Practices-Techniques for Reducing Non-Point Source Pollution in the Coastal Zone.	Seattle, WA	--	--	--	--	87	78	Concentration Basis
"	Boynton Beach	--	--	--	--	91	--	"
"	Grace Street	--	--	--	--	32	12	"
"	Pitt-AA	--	--	--	--	32	18	"
"	Unqua	--	--	--	--	60	45	"
"	Waverly Hills	--	--	--	--	91	79	"
"	Lake Ellyn, IL	--	--	--	--	84	34	"
"	Lake Ridge, MN	--	--	--	--	88	49	"
"	West Pond, MN	--	--	--	--	25	--	"
"	McCarrons, MN	--	--	--	--	78	--	"

Wet Basins (cont'd)								
Source	**ID**	**Inflow [TSS}**	**Outflow [TSS]**	**Inflow [P]**	**Outflow [P]**	**% TSS removed**	**% P removed**	**Comment**
Metropoliton Washington Council of Governments, 1992. A Current Assessment of Urban Best Management Practices-Techniques for Reducing Non-Point Source Pollution in the Coastal Zone.	McKnight Basin, MN	--	--	--	--	41	13	Concentration Basis
"	Monroe St., WI	--	--	--	--	65	70	"
"	Runaway Bay, NC	--	--	--	--	24	--	"
"	Buckland, CT	--	--	--	--	61	45	"
"	Highway Site, FL	--	--	--	--	65	17	"
"	Woodhollow, TX	--	--	--	--	54	46	"
"	SR204, WA	--	--	--	--	99	91	"
"	Farm Pond, VA	--	--	--	--	85	86	"
"	Burke, VA	--	--	--	--	-33	39	"
"	Westleigh, MD	--	--	--	--	81	54	"
"	Mercer, WA	--	--	--	--	75	67	"
"	I-4, FL	--	--	--	--	54	69	"
"	Timber Creek, FL	--	--	--	--	64	60	"
"	Lakeside, NC	--	--	--	--	91	23	"

Appendix B3. Constructed Wetlands

Constructed Wetlands								
Source	**ID**	**Inflow [TSS}**	**Outflow [TSS]**	**Inflow [P]**	**Outflow [P]**	**% TSS removed**	**% P removed**	**Comment**
Winer, Nat'l Poll. Rem. Database, 2000	#57	--	--	--	--	93	76	Mass Basis
"	#59	45	42	0.17	0.19	7	-12	Concentration Basis
"	#61	123.6	26.9	0.447	0.11	78	75	Concentration Basis
"	#61	--	--	--	--	78	79	Mass Basis
"	#62	--	--	--	--	61	33	Mass Basis
"	#62	--	--	--	--	50	28	Concentration Basis
"	#63	--	--	--	--	68	62	Mass Basis
"	#64	74.7	20.8	0.35	0.26	72	26	Concentration Basis
"	#64	--	--	--	--	96	70	Mass Basis
"	#65	--	--	--	--	66	4	Mass Basis
"	#67	134	33	0.45	0.201	75	55	Concentration Basis
Forbes, 2004 #80	--	--	--	--	--	--	9	Concentration Basis
"	--	--	--	--	--	--	16	Concentration Basis
"	--	--	--	--	--	--	21	Concentration Basis
"	--	--	--	--	--	--	47	Concentration Basis
"	--	--	--	--	--	--	62	Concentration Basis

Constructed Wetlands (cont'd)

Source	ID	Inflow [TSS}	Outflow [TSS]	Inflow [P]	Outflow [P]	% TSS removed	% P removed	Comment
Forbes, 2004 #80	--	--	--	--	--	--	51	Concentration Basis
Bulc, 2003 #52	--	42	11	0.4	0.1	74	75	Concentration Basis
ASCE, 2002 #81	--	--	--	--	--	--	23	Concentration Basis
"	--	--	--	--	--	--	61	Concentration Basis
"	--	--	--	--	--	--	34	Concentration Basis
"	--	--	--	--	--	--	45	Concentration Basis
"	--	--	--	--	--	--	29	Concentration Basis
Caltrans 2004 BMP Retrofit Pilot Program Final Report App F	LaCosta WB	--	--	--	--	91	2	Concentration Basis
Carleton, Grizzard, Godrej, Post, Lampe, and Kenel, 2000. Performance of a constructed wetlands in treating urban stormwater runoff. Water Environ. Research 72(3):295-304.	Franklin Farms	--	--	--	--	93	76	For storms < wetland capacity. Mass Basis
"	Crestwood	--	--	--	--	58	46	Median - Mass Basis
Dierberg, DeBusk, Jackson, Chimney, Pietro, 2002. Submerged aquatic vegetation-based treatment wetlands for removing phosphorus from agricultural runoff: response to hydraulic and nutrient loading. Water Research 36.	1.5 day HRT	--	--	--	--	--	51	Concentration Basis
"	3.5 day HRT	--	--	--	--	--	73	Concentration Basis
"	7 day HRT	--	--	--	--	--	79	Concentration Basis
Oberts, 1994. Performance of Stormwater Ponds and Wetlands in Winter. In "Watershed Protection Techniques," Vol 1(2), Center for Watershed Protection.	--	--	--	--	--	82	68	Unknown Basis

Constructed Wetlands (cont'd)

Source	ID	Inflow [TSS}	Outflow [TSS]	Inflow [P]	Outflow [P]	% TSS removed	% P removed	Comment
Oberts, 1994. Performance of Stormwater Ponds and Wetlands in Winter. In "Watershed Protection Techniques," Vol 1(2), Center for Watershed Protection.	--	--	--	--	--	4	7	Unknown Basis
BMP Database. Site: Franklin Wood, Chantilly, VA	--	--	--	--	--	--	5	Concentration Basis
BMP Database. Franklin Wetland, Chantilly, VA	--	--	--	--	--	--	23	Concentration Basis
BMP Database. Site: Hidden River Wetland, Tampa, FL	--	--	--	--	--	--	61	Concentration Basis
BMP Database. Site: Queen Anne's Pond, Centreville, MD	--	--	--	--	--	--	34	Concentration Basis
BMP Database. Site: Swift Run Wetland, Ann Arbor, MI	--	--	--	--	--	--	45	Concentration Basis
Metropoliton Washington Council of Governments, 1992. A Current Assessment of Urban Best Management Practices-Techniques for Reducing Non-Point Source Pollution in the Coastal Zone.	EWA3, IL	--	--	--	--	72	59	Unknown Basis
"	EWA4, IL	--	--	--	--	76	55	Unknown Basis
"	EWA5, IL	--	--	--	--	89	69	Unknown Basis
"	EWA6, IL	--	--	--	--	98	79	Unknown Basis
"	B31, WA	--	--	--	--	14	-2	Unknown Basis
"	PC12, WA	--	--	--	--	56	-2	Unknown Basis
"	McCarrons, MN	--	--	--	--	87	36	Unknown Basis
"	Queen Anne's, MD	--	--	--	--	65	39	Unknown Basis
"	Swift Run, MI	--	--	--	--	85	3	Unknown Basis
"	Tampa Office Pond, FL	--	--	--	--	64	55	Unknown Basis
"	Highway Site, FL	--	--	--	--	66	19	Unknown Basis
"	Palm Beach, PGA, FL	--	--	--	--	50	62	Unknown Basis

Appendix B4. Bioretention Filters

Bioretention Filters

Source	ID	Inflow [TSS}	Outflow [TSS]	Inflow [P]	Outflow [P]	% TSS removed	% P removed	Comment
Winer, Nat'l Poll. Rem. Database, 2000	#93	--	--	0.52	0.18	--	65.38	Concentration Basis
Winer, Nat'l Poll. Rem. Database, 2000	#93	--	--	--	--	--	65	Mass Basis
Idaho DEQ BMP Manual (undated)	--	--	--	--	--	90	75	unknown
Caltrans 2002 as ref'd in "Bioretention TC32," found in CA Stormwater BMP Handbook Developement & Redevelopment at http://www.cabmphandbooks.com/Development.asp	--	--	--	--	--	90	76	unknown
Low Impact Development (LID) A Literature Review, EPA-841-B-00-005. USEPA, Oct. 2000	Beltway Plaza, Greenbelt, MD	--	--	--	--	--	65	unknown
Low Impact Development (LID) A Literature Review, EPA-841-B-00-005. USEPA, Oct. 2000	Peppercorn Plaza, Landover MD	--	--	--	--	--	87	unknown

Appendix B5. Sand Filters

Sand Filters								
Source	**ID**	**Inflow [TSS}**	**Outflow [TSS]**	**Inflow [P]**	**Outflow [P]**	**% TSS removed**	**% P removed**	**Comment**
Winer, Nat'l Poll. Rem. Database, 2000	#101	76.2	16.84	0.52	0.18	78	65	Concentration Basis
"	#101	--	--	--	--	79	66	Mass Basis
"	#102	16.1	10.3	0.08	0.06	36	25	Concentration Basis
"	#103	97.2	11.8	0.123	0.065	88	47	Concentration Basis
"	#104	204	3.5	0.356	0.126	98	65	Concentration Basis
"	#104	--	--	--	--	98	66	Mass Basis
"	#105	--	--	--	--	87	61	Mass Basis
"	#106	--	--	--	--	92	80	Mass Basis
"	--	--	--	--	--	--	--	Mass Basis
"	--	--	--	--	--	--	--	Mass Basis
"	#107	--	--	--	--	75	59	Mass Basis
"	#108	--	--	--	--	86	19	Mass Basis
"	#109	273	32	0.37	0.11	88	70	Concentration Basis
"	#110	--	--	--	--	98	61	Mass Basis
"	#111	--	--	--	--	78	27	Mass Basis
"	#112	449	112	0.4	0.14	75	65	Concentration Basis
"	#113	--	--	--	--	60	--	Mass Basis

Sand Filters (cont'd)

Source	ID	Inflow [TSS}	Outflow [TSS]	Inflow [P]	Outflow [P]	% TSS removed	% P removed	Comment
Division, 1990 #79	--	--	--	--	--	--	0	Concentration Basis
"	--	--	--	--	--	--	45	Concentration Basis
"	--	--	--	--	--	--	59	Concentration Basis
Caltrans 2004 BMP Retrofit Pilot Program Final Report App F	E Reg MS	--	--	--	--	75	23	Concentration Basis
Glick, et al, 1998. Referenced in above report (pg 2-10)	--	--	--	--	--	89	59	Concentration Basis
Caltrans 2004 BMP Retrofit Pilot Program Final Report App F	Foothill MS	--	--	--	--	86	21	Concentration Basis
Caltrans 2004 BMP Retrofit Pilot Program Final Report App F	Term P&R	--	--	--	--	89	24	Concentration Basis
Caltrans 2004 BMP Retrofit Pilot Program Final Report App F	Escon MS	--	--	--	--	58	37	Concentration Basis
Caltrans 2004 BMP Retrofit Pilot Program Final Report App F	LaCosta P&R	--	--	--	--	91	30	Concentration Basis
Caltrans 2004 BMP Retrofit Pilot Program Final Report App F	SR78/I%P&R	--	--	--	--	87	29	Concentration Basis
Glick, et al, 1998. Monitoring and evaluation of stormwater quality control basins in watershed mgt: Moving from theory to	--	--	--	--	--	89	59	Concentration Basis
Environ & Conservation Services Dept. Austin TX. Removal Efficiencies of Stormwater Control Structures. May 1990.	Highwood Apt	--	--	--	--	86	19	Mass Basis
Environ & Conservation Services Dept. Austin TX. Removal Efficiencies of Stormwater Control Structures. May 1990.	Barton Creek Squ. Mall	--	--	--	--	75	59	Mass Basis
Environ & Conservation Services Dept. Austin TX. Removal Efficiencies of Stormwater Control Structures. May 1990.	Jollyville	--	--	--	--	87	61	Mass Basis

Appendix B6. Filter Strips/Grass Swales

Filter Strips/Grass Swales

Source	ID	Inflow [TSS}	Outflow [TSS]	Inflow [P]	Outflow [P]	% TSS removed	% P removed	Comment
Barrett, Walsh, Malina and Charbeneau, 1998. Performance of Vegetative Controls for Treating Highway Runoff. Jour. Environ. Engrg. 1121-1128. US 183 median.	US 183	157	21	0.55	0.31	87	44	Concentration Basis/Grassy Median
"	MoPac expway	190	29	0.24	0.16	85	33	Concentration Basis/Grassy Median
BMP Data Base. Austin, TX. Site: Alta Vista planned development det. w/ swales	--	--	--	--	--	29	84	Concentration Basis/Grassy Median
EPA Data Base: Dayton Swale - Dayton Biofilter with grassed Swale (Site ID 1645113921)	--	--	--	0.183	0.192	--	-5	"
BMP Data Base, Seattle. Site: Dayton Biofilter-Grass Swale	--	--	--	--	--	--	-5	"
"Field Test of Grassed Swale Performance in Removing Runoff Pollution," by Jan-Tai Kuo, Shaw L. Yu et al. University of VA	Goose Creek-upper	--	--	--	--	29.7	73.4	Mass Basis/Swale
"	Goose Creek-lower	--	--	--	--	97.2	96.8	Mass Basis/Swale
"	Goose Creek-entire	--	--	--	--	94	98.6	Mass Basis/Swale
Caltrans 2002 as ref'd in "Vegetative Swale TC30," found at http://www.cabmphandbooks.com/Development.asp	--	--	--	--	--	77	8	Mass Basis/Dry Swale
Goldberg, 2003 as ref'd in "Vegetative Swale TC30," found at http://www.cabmphandbooks.com/Development.asp	--	--	--	--	--	67.8	4.5	Mass Basis/Grassed Channel
Seattle Metro & Washington Dept. of Ecology, 1992 as ref'd in "Vegetative Swale TC30," found at http://www.cabmphandbooks.com/Development.asp	--	--	--	--	--	60	45	"
"	--	--	--	--	--	83	29	"

Filter Strips/Grass Swales (cont'd)

Source	ID	Inflow [TSS}	Outflow [TSS]	Inflow [P]	Outflow [P]	% TSS removed	% P removed	Comment
Wang et al., 1981 as ref'd in "Vegetative Swale TC30," found in CA Stormwater BMP Handbook Developement & Redevelopment at http://www.cabmphandbooks.com/Development.asp	--	--	--	--	--	80	--	Mass Basis/Dry Swale
Dorman et al., 1989 as ref'd in "Vegetative Swale TC30," found in CA Stormwater BMP Handbook Developement & Redevelopment at http://www.cabmphandbooks.com/Development.asp	--	--	--	--	--	98	18	"
Harper, et al., 1988 as ref'd in "Vegetative Swale TC30," found in CA Stormwater BMP Handbook Developement & Redevelopment at http://www.cabmphandbooks.com/Development.asp	--	--	--	--	--	87	83	"
Kercher et al., as ref'd in "Vegetative Swale TC30," found in CA Stormwater BMP Handbook Developement & Redevelopment at http://www.cabmphandbooks.com/Development.asp	--	--	--	--	--	99	99	"
Harper, et al., 1988 as ref'd in "Vegetative Swale TC30," found in CA Stormwater BMP Handbook Developement & Redevelopment at http://www.cabmphandbooks.com/Development.asp	--	--	--	--	--	81	17	Mass Basis/Wet Swale
Koon, 1995 as ref'd in "Vegetative Swale TC30," found in CA Stormwater BMP Handbook Developement & Redevelopment at http://www.cabmphandbooks.com/Development.asp	--	--	--	--	--	67	39	"
City of Austin. 1995 (draft). Characterization of Stormwater Pollution for the Austin, Texas Area. Environmental Resources Management Division, Environmental and Conservation Services Department, City of Austin, Austin, Texas. As found at http://www.fhwa.	--	--	--	--	--	68	43	Concentration Basis
Yu, S.L., S.L. Barnes, and V.W. Gerde. 1993. Testing of Best Management Practices for Controlling Highway Runoff. Virginia Department of Transportation, Report No. FHWA/VA-93-R16, Richmond, VA. As found at http://www.fhwa.dot.gov/environment/ultraurb/3fs1	--	--	--	--	--	49	33	Mass Basis

Filter Strips/Grass Swales (cont'd)								
Source	**ID**	**Inflow [TSS}**	**Outflow [TSS]**	**Inflow [P]**	**Outflow [P]**	**% TSS removed**	**% P removed**	**Comment**
Yu, S.L., and R.J. Kaighn. 1995. The Control of Pollution in Highway Runoff Through Biofiltration. Volume II: Testing of Roadside Vegetation. Virginia Department of Transportation, Report No. FHWA/VA-95-R29, Richmond, VA. As found at http://www.fhwa.dot.g	--	--	--	--	--	30	0	Concentration Basis
Khan, Z., C. Thrush, P. Cohen, L. Kulzer, R. Franklin, D. Field, J. Koon, and R. Horner. 1992. Biofiltration Swale Performance, Recommendations, and Design Considerations. Municipality of Metropolitan Seattle, Water Pollution Control Department, Seattle,	--	--	--	--	--	83	29	Mass Basis
FHWA, 1996. Evaluation and Management of Highway Runoff Water Quality. FHWA-PD-96-032.	--	--	--	--	--	83	29	Mass Basis/200 ft swale
"	--	--	--	--	--	60	45	Mass Basis/100 ft swale
Winer, Nat'l Poll. Rem. Database, 2000	#127	--	--	--	--	67.8	4.5	Concentration Basis/Grassed Channel
Winer, Nat'l Poll. Rem. Database, 2001	#128	--	--	--	--	83	29	"
Winer, Nat'l Poll. Rem. Database, 2002	#129	--	--	--	--	60	45	"
Winer, Nat'l Poll. Rem. Database, 2003	#130	--	--	--	--	81	17	Mass Basis/Wet Swale
Winer, Nat'l Poll. Rem. Database, 2004	#131	--	--	--	--	67	39	Concentration Basis/Wet Swale
Winer, Nat'l Poll. Rem. Database, 2000	#126	--	--	--	--	80	--	Mass Basis/Dry Swale
Winer, Nat'l Poll. Rem. Database, 2000	#123	--	--	--	--	98	18	"
Winer, Nat'l Poll. Rem. Database, 2001	#124	--	--	--	--	87	83	"
Winer, Nat'l Poll. Rem. Database, 2002	#125	--	--	--	--	99	99	"

Appendix B7. Infiltration Trenches

Infiltration Trenches								
Source	**ID**	**Inflow [TSS}**	**Outflow [TSS]**	**Inflow [P]**	**Outflow [P]**	**% TSS removed**	**% P removed**	**Comment**
Winer, Nat'l Poll. Rem. Database, 2000	Study 132	--	--	0.66	0.63	--	4.5	--
Winer, Nat'l Poll. Rem. Database, 2000	Study 133	--	--	0.2	0	--	100.0	--
Winer, Nat'l Poll. Rem. Database, 2000	Study 134	--	--	0.24	0	--	84.0	--
IDAHO BMP Manual	--	--	--	--	--	90	55	--