Modeling Arid, Urbanized Watersheds: Part I, Hydrologic Modeling

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ABSTRACT

Time-variable models of arid, urbanized watersheds are rare, but are becoming necessary to estimate unmonitored area emissions and predict management scenario effectiveness. In this study, the time-variable model HSPF is developed using 15 min increments to estimate flows and volumetric loads to Santa Monica Bay (SMB). The model used locally generated data including detailed land use, rainfall, watershed delineations, and stream geometry. An open watershed calibrated it using flow and rainfall between 1988 and 1998. The model was validated on an urbanized watershed during the same period and compared well to empirical flow data (r^2=0.84).

An estimated 8.41×10^{10} m^3 of runoff enters SMB during an average year. Urbanized subwatersheds contributed a disproportionate amount of volume (60%) relative to their area (43%). Rainfall variability did not result in proportional linear increases in volumes. Rainfall in extreme wet years was 187 % of normal, but resultant volumes exceeded the median by 217% to 1149%. While the model accurately simulated peak flows, it had difficulty with low flows and transitioning from low flows to no flow conditions.

INTRODUCTION

Environmental managers around the country are faced with resolving large water quality problems associated with urban wet weather runoff (U.S. EPA 1998). One problem, in particular, is estimating volumes of stormwater runoff when no empirical monitoring data are available. The problem of estimating unmonitored flows is exacerbating in complex watersheds where there are a variety of factors that influence surface flows. One such watershed is Santa Monica Bay (SMB) in Southern California (Figure 1). The SMB watershed has a wide variety of characteristics. Subwatersheds to the north are comprised of national forest and are almost entirely open. Subwatersheds to the south encompass portions of downtown Los Angeles and are almost entirely urbanized. Most surface water flows in the urbanized portions of the watershed are either routed in underground pipes or are conveyed in large, concrete-lined channels. Only two subwatersheds (Ballona and Malibu Creeks) for the entire SMB are currently monitored representing 58% of the total watershed area.

The water quality problems associated with wet weather in SMB appear to be amplified due to its arid environment. Not only are portions of SMB extremely urbanized, but rainstorms are infrequent enabling pollutants to build-up for longer time periods between storm events. The wet season in southern California extends from October to April. Evaluation of long-term rainfall records has shown that the area receives only 12 storm events per year with the majority (ca. 45% on average) of precipitation occurring in January and February (Stenstrom and Strecker 1993). Moreover, when it does rain, the events can produce large flows that increase from < 1 cfs to > 10,000 cfs in less than 2 hours (Tiefenthaler *et al* 2001). In contrast, most channels are completely dry the remainder of the year.

Static models have been developed to estimate loadings to SMB from unmonitored areas and flows (Ackerman and Schiff 2001, Wong *et al* 1997, Escobar 1999a). Static models often employ the Rational Method (U.S. EPA 1992) and are relatively easy to apply on an annual basis; model calibrations improve on longer time scales (i.e. 5 – 10 years). Static models rely upon readily available information including land use, rainfall and stream flow to estimate volumetric loadings. However, they are limited in their ability to estimate the behavior of systems on short (minutes or hours) time scales. Moreover, they necessarily make several large assumptions. For example, they do not differentiate antecedent conditions nor incorporate water cycling in simulating anything more than direct runoff (i.e. no baseflow is simulated).

Environmental managers in the SMB have started turning to models as a means of estimating wet weather pollutant contributions from unmonitored areas, but also as a predictive tool to help evaluate different management scenarios for reducing or eliminating their water quality problems. This has largely precipitated from the development and implementation of total maximum daily loads (TMDLs). TMDLs require not only the estimate of loading, but also an assessment of efficient and effective management measures. Unfortunately, models that oversimplify complex hydrologic, hydrodynamic and water quality behaviors are inadequate for making these predictive assessments.

Environmental managers are favoring dynamic models for predictive assessments because they are time variable and simulate watershed behavior with increased accuracy. For example, antecedent conditions are incorporated in runoff calculations for any event throughout the simulation. Dynamic models also incorporate groundwater movement and simulate baseflow. Finally, they can be used for investigating the inter- and intra-storm behavior of a system. These characteristics are extremely useful because many best management practices in urban landscapes are affecting only portions of a storm (i.e. the first ¼ inch of rainfall or the first 10% of storm flows) or are focused on specific storm events (i.e. the first storm of the year or all storm with 1-2 year return frequency).

The goal of this study was to develop a dynamic hydrologic model for the SMB watershed and estimate volumetric loadings during a typical year. Understanding the changes in flow among and within storm events is fundamental before managers can expect to model improvements in water quality. The uniqueness of this study lies in the application. First, the dynamic model is applied to an arid watershed where perennial flowing streams may not exist. Second, the dynamic model is applied using rapid time steps (15 min) since storms in this arid region are of short duration and potential management actions must necessarily occur on these time scales.

METHODS

The Hydrologic Simulation Program – FORTRAN (HSPF) (Bicknell *et al* 1997) was selected for this study. A five-step process was used to estimate volumetric loading to Santa Monica using HSPF. First, the appropriate data was collected for calibration and validation. Second, the modeling assumptions were defined. The third and fourth steps involved calibration and validation of the model. Fifth, the model was applied to all the watersheds in SMB to estimate an annual volumetric load.

Data

Six types of data were gathered for model development including: (1) meteorological; (2) hydrologic; (3) land use; (4) topography; (5) point source discharge; and (6) stream flow data. Meteorological data (precipitation, temperature, dew point, wind speed, cloud cover, etc.) from the BASINS core data set (U. S. EPA 2001) was supplemented with data from the Los Angeles International Airport (LAX) (NCDC 2001a). Additional precipitation data from the Los Angeles County Department of Public Works (LACDPW), including their Alert network was also used (Brown 2001). Measured 30-year precipitation, in conjunction with topography, was used to extrapolate rainfall to unmonitored watersheds (PRISM 1999). Stream flow measurements for Ballona and Malibu Creeks were obtained for 1990 – 1999 (USGS 2001 and Kwan 2001). Discharge records from the local wastewater reclamation facility were acquired from the Los Angeles Regional Water Quality Control Board (Elliott 2001).

Twenty-eight subwatersheds were delineated in SMB (Figure 1). Watersheds were delineated by combining data from the California Department of Fish and Game (1999) watersheds and stormdrain/stormshed networks from LACDPW (Escobar 2000). In addition, the data from the LACDPW was used to define stream networks and geometry.

A detailed land use data set was obtained and aggregated from 43 to 13 land use categories (Table 1) (Escobar 1999b). In addition to the 28 subwatersheds, SMB was divided into northern and southern bay watersheds based upon degree of urbanization. In total, the North Bay was 87% non-urbanized and the South Bay 82% urbanized.

Assumptions

As with any modeling effort, assumptions were necessary to mimic complex natural processes. Four main assumptions were made about the SMB system: 1) only flows associated with stormwater-related runoff and point sources were modeled; 2) the system was homogenous within land use types; 3) the overflow dynamics of the monitored dam in the Malibu watershed was applicable to two other dams in the same watershed; and 4) the calibrated and validated model from monitored watersheds was applicable in unmonitored watersheds.

We assumed that there were no additional non-point sources of dry weather inputs where data was unavailable. The southern watersheds in the SMB are highly urbanized and non-point, dry weather flows can contribute to stream flow throughout most of the year. These flows exist during extended dry periods and are not associated with a rain event.

For the major watersheds (Ballona and Malibu Creeks) data existed, but non-point source activities within the other subwatersheds was unknown. Since we could not quantify the volume and flow rate of these nuisance flows, we assumed they were negligible and did not include them in the model. The assumption appears warranted since dry weather flows in Ballona Creek, where nuisance flows are monitored, represents less than 2% of the annual discharge volume.

We assumed that the basic soil and land use runoff characteristics were not significantly different within the region. The runoff model defines land as either pervious or impervious. The pervious (hardened) are assumed to be consistent throughout the region. For the impervious portions, we also assumed that the basic runoff characteristics were the same in the SMB based upon soil surveys (U. S. EPA 2001).

Three lakes in the Malibu Creek watershed were included in the model. A flow-rating table existed for Malibu Lake. The flow-rating table was extrapolated from Malibu Lake to the others by changing weir lengths and applying the weir equation (LARWQCB 2001 and Tetra Tech 2001). We assumed that the overflow characteristics of the remaining two lakes, Sherwood and Westlake, were similar to Malibu Lake.

Our final assumption was that the calibrated and validated model was applicable in unmonitored watersheds. The hydrologic model was calibrated and validated in watersheds of comparable size, but of very different land use composition. The calibration and validation watersheds were representative of the open areas (Malibu

Creek) and highly urbanized (Ballona Creek). The model performed well in those watersheds and model transference to other watersheds was assumed appropriate.

Calibration and validation

The model was calibrated using 10 years (Oct 1988 to Sept 1998) of flow at the gage located furthest downstream in the Malibu Creek. The gage captures runoff from 272 km^2, or roughly 52% of the watershed. The watershed is approximately 86% undeveloped and largely pervious, thus more sensitive than the Southern watersheds to the HSPF parameters. Model parameters were adjusted universally within each land use type (i.e. no differences between land use types among subwatersheds). Model calibration was performed using the HSP Expert system (Lumb *et al* 1994) and compared to measured data.

The model was validated using 10 years (Oct 1988 to Sept 1998) of flow at the flow gage located furthest downstream in the Ballona Creek watershed. The gage captures runoff from 230 km^2, or roughly 44% of the watershed. Unlike Malibu Creek, Ballona Creek watershed is approximately 88% developed and largely impervious, thus a distinctly different watershed than Malibu Creek. However, all of the HSPF parameter values from the calibration watershed were used for the validation watersheds. Another dissimilarity among the calibration and validation watersheds was the presence of a non-point source base flow. To account for these flows, 14 cfs was added to the upstream end of the system based on historic average dry flow during the summer months of June through

August during the simulation period. Model validation runs were compared to measured data.

Application

The calibrated and validated model was applied to the 28 watersheds in the SMB to estimate volumetric loadings. Long-term rainfall analysis was based on 54 years (1947 – 2000) of rainfall data at LAX. Simulations were made for the median year (1991) and the 10^{th} and 90^{th} percentile years (1990 and 1993, respectively) (NCDC 2001b). Sensitivity analysis was conducted for changes in rainfall by examining predicted runoff for the 10^{th} and 90^{th} percentile rainfall years from 1947 to 1998.

RESULTS

Calibration

The Malibu Creek watershed calibrated well to historical flow data. Percent impervious was determined for each of the modeled land uses (Table 1) and model parameters were optimized to reflect flows observed throughout the 10-year simulation period (Table 2).

Modeled estimates of annual volume were within 1% of measured volumes over the calibration time period. Moreover, the model accurately predicted daily flows with reasonable accuracy (Figure 2). The model correctly identified 9 out of 10 days with the greatest peak flows during the simulation period. This occurred regardless of a relatively dry (1992) or wet (1998) year.

There was good correspondence among modeled and measured storm flows (Figure 2). The model could predict 88% of the variability in daily average flow measurements during storm events occurring between 1988 and 1998 in this watershed. Modeled estimates were biased low, on average, by 21%.

Validation

The Ballona Creek watershed validated well to historical flow data. Modeled estimates of annual volume were within 7% of measured volumes over the calibration time period. Moreover, the model accurately predicted daily flows with reasonable accuracy (Figure 3). The model correctly identified the 9 out of 10 days with the greatest peak flows during the simulation period. This occurred regardless of a relatively dry (1992) or wet (1998) year.

There was good correspondence among modeled and measured storm flows (Figure 3). The model could predict 84% of the variability in daily average flow measurements during storm events occurring between 1988 and 1998 in this watershed. Modeled estimates were biased high, on average, by about 1%.

Application

An estimated 1.13×10^{11} L of wet weather runoff is delivered to SMB during an average water year (Figure 4). Urbanized subwatersheds accounted for a disproportionate amount of this volume; seven of the top nine subwatersheds were from the urbanized South Bay region. South Bay subwatersheds accounted for 43% of the total land area and 60% of the total volumetric input to the SMB.

Sensitivity of the hydrologic model was tested by examining extreme (10^{th} and 90^{th} percentile) rainfall years (Figure 4). The variation among years ranged from 63% (7.10×10^{10} m^3) to 293 % (3.33×10^{11} m^3) of the average wet year. Open watersheds generally had a wider range of variability than urban watersheds. For example, the greatest variability in one of the nonurban watersheds from the North Bay ranged from 44 to 1096% of the average water year. In contrast, the greatest variability in one of the urban watersheds from the South Bay ranged from 55 to 746% of the average water year.

The SMB is an arid watershed with the majority of flow occurring during a minor proportion of the year (Figure 5). More than 99% of the annual volume was discharged during less than 15% of the year. Even during relatively wet years, the relative differences in dry and wet weather discharge volumes do not change. A second component of arid watersheds is the drastic changes in flows. Cumulatively for SMB, the 28 watersheds have low flows near 25 cfs. However, average daily flows during our short-term storm events peak more than two orders of magnitude higher at 5,000 cfs.

DISCUSSION

The wet weather model was successfully applied to arid and urban watersheds with intermittent streams. The watersheds in the SMB are representative of many watersheds throughout Southern California and other arid cities reflecting a wide range of characteristics from highly urbanized to almost completely nonurban. Regardless of its land use characteristics, we were able to estimate stormwater flows with reasonable accuracy. Because flows and volumes can be recreated system wide, the next steps in the modeling process can be taken; the modeling of water quality.

Although the model was able to recreate wet weather conditions, the model had difficulty with estimating flows during extended dry periods or transitioning from wet to dry streams. This may have resulted from one of three reasons. First, an incomplete understanding of the dam operating schedules may have impaired low flow estimates in Malibu Creek. A flow-rating curve was only available for one of the lakes in the watershed and curves for the other lakes were extrapolated from that understanding. Second, unmonitored releases occur during the long dry periods in urban watersheds. A good example is illustrated by the Ballona Creek subwatershed. A baseflow of 14 cfs was measured in the watershed that is not attributable to rainfall, groundwater flow or point source discharges; it is the result of nonpoint sources within the watershed. The baseflow information was included in the volumetric loading for Ballona Creek because data existed to estimate it. In the other watersheds however (with the exception of

Malibu Creek), no long-term baseflow measurements were available to estimate the non-point dry weather flows. Other investigators need to be aware of this concern as they attempt to model their arid urban watersheds. Finally, the model showed some instability during the transition from very low flow to dry streams. This issue will become especially significant when trying simulate water quality. To alleviate this condition, we set a lower flow limit on the model output of 0.01 cfs.

Utilizing detailed local information was critical in accurately estimating stream flows, particularly in urban areas. We used the core data set included in the BASINS package as a reference point. We found that while the data set provided a minimum of information, it was necessary to supplement that with local land use and precipitation data. The local data vastly improved land use resolution and accuracy, dramatically improving our ability to conduct simulations. Other investigators will likely find, as we did, that changes in land use from rapidly developing subwatersheds is a common problem in large urban centers like SMB. Likewise, we used local rain gage and long-term modeled rainfall patterns to better estimate the spatially variable rainfall throughout the region. This is of particular importance in SMB where 2-fold rainfall gradients occur as a result of topography (300 m in 4.5 km).

Not unexpectantly, we found that urban watersheds were sensitive to small rain events because of their imperviousness. Similarly, small-scale spatial variability in rainfall was an important concern when modeling urban subwatersheds. The relatively intensive local rain gage network, which amounted to 5 gages within our study area, improved our ability to model hydrology in the SMB watershed. However, even greater spatial resolution would have improved our simulations. We investigated using NEXRAD data to supplement the rainfall form local gages. While this appears to be a promising technique, we could not use it in SMB because of limitations in the local NEXRAD information.

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Figure 1. Site map of Santa Monica Bay showing the location of rain gages, USGS stream gages, watershed delineations, Los Angeles International Airport (LAX), and Tapia Water Reclamation Plant.

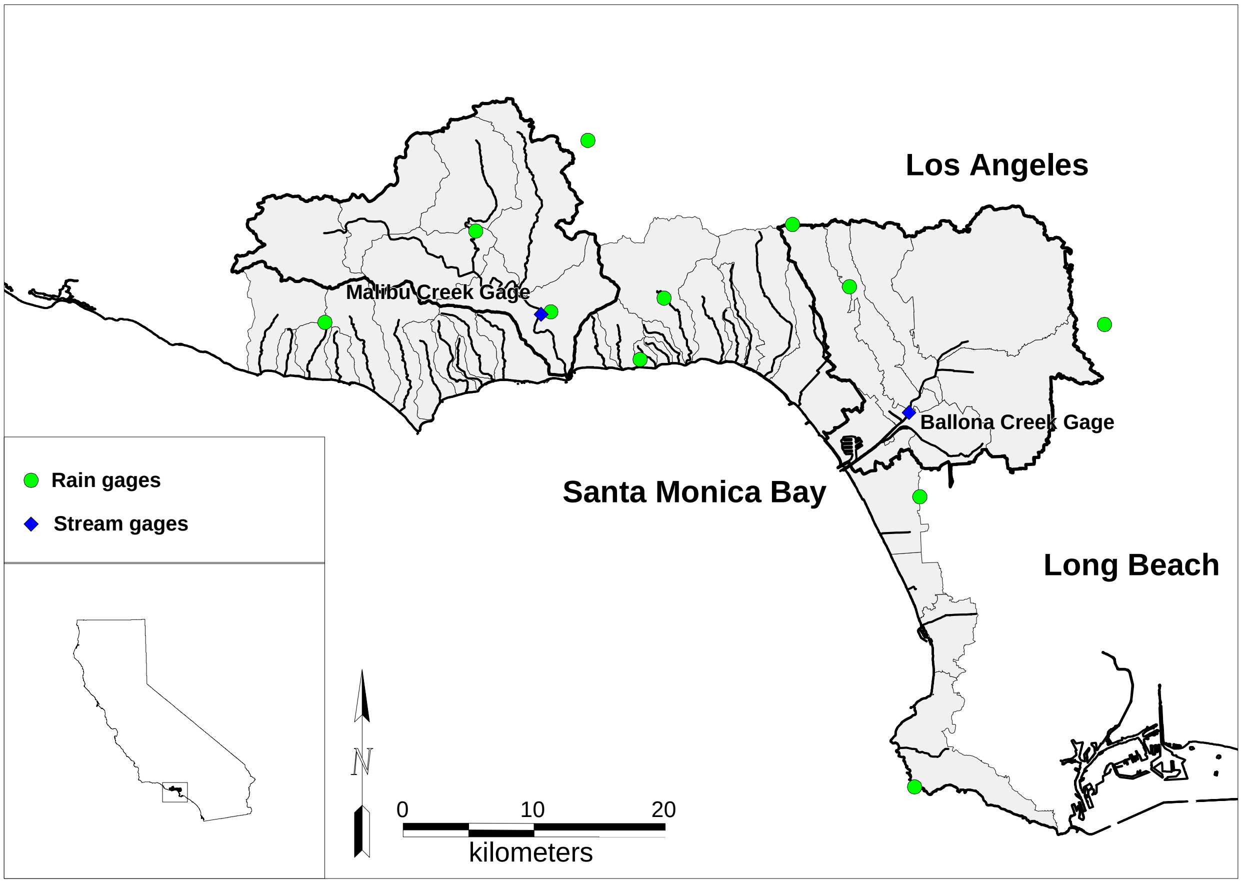
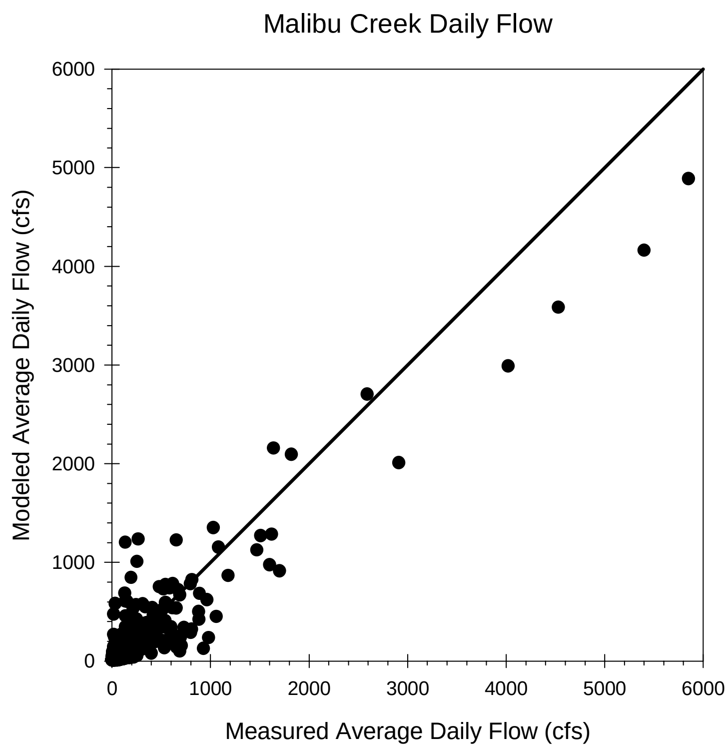


Figure 2. Comparison of Malibu Creek daily (a) and storm flows (b).



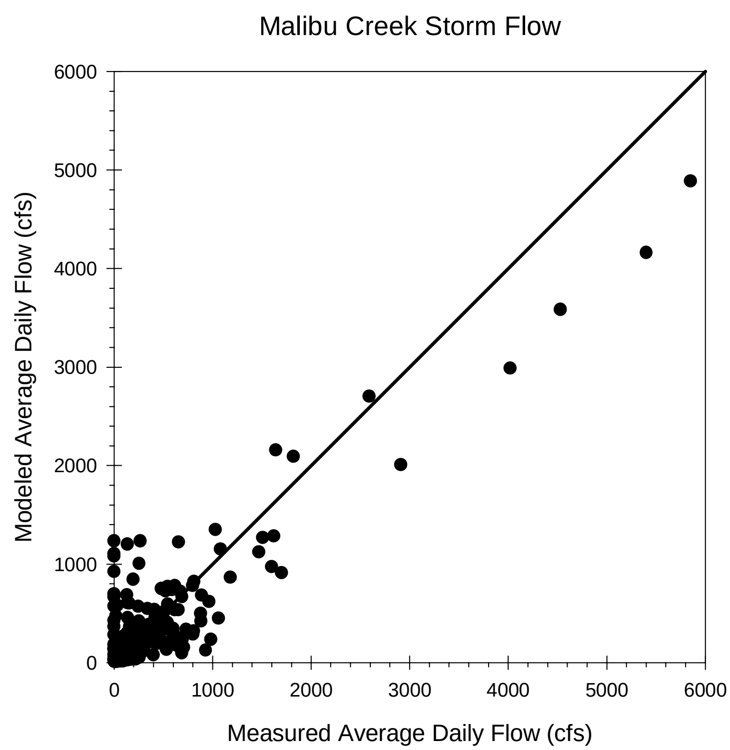
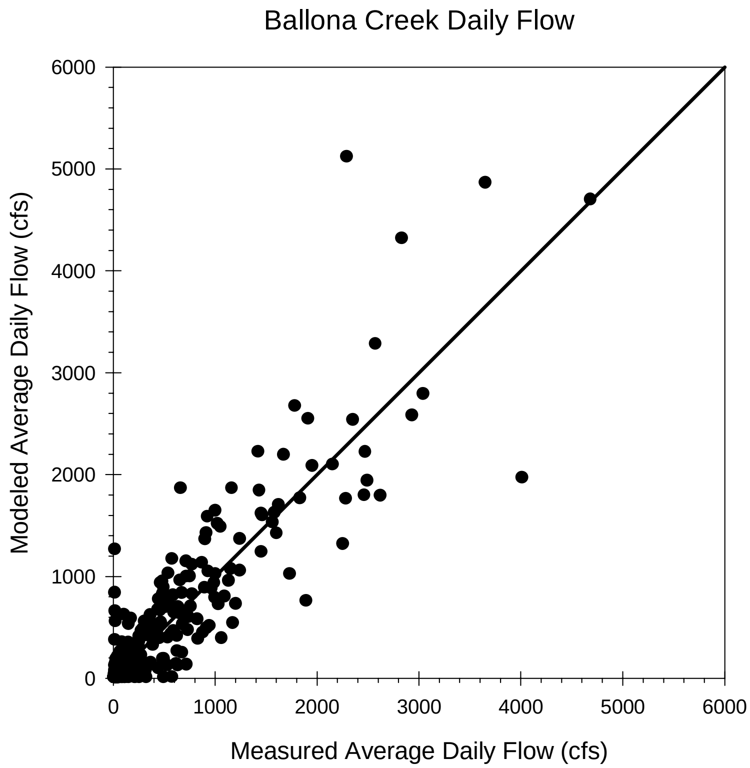


Figure 3. Comparison of Ballona Creek daily (a) and storm flows (b).



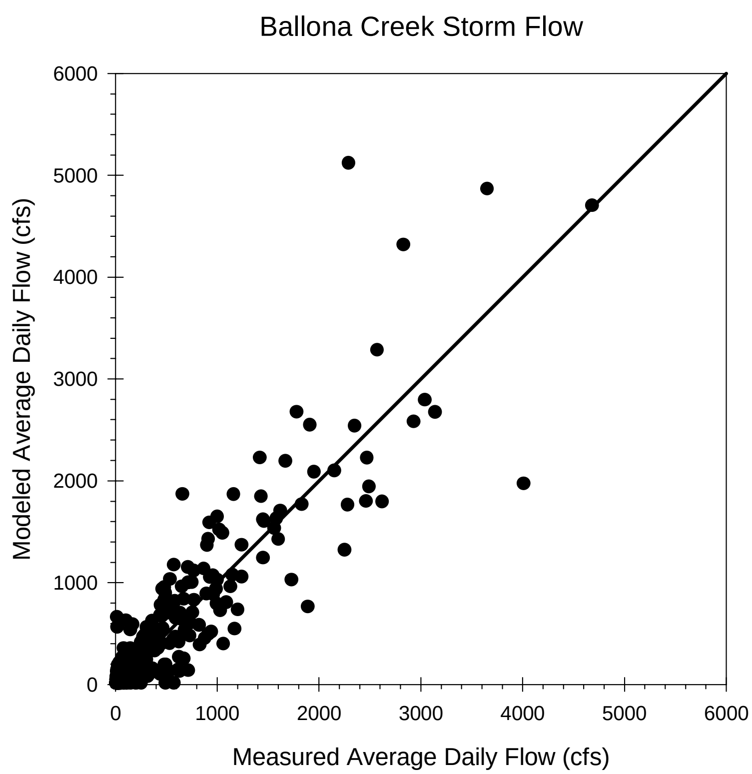


Figure 4. Annual wet weather volumetric loading for the median water year (error bars represent 10^{th} and 90^{th} percentile) between 1947 and 1998 in Santa Monica Bay.

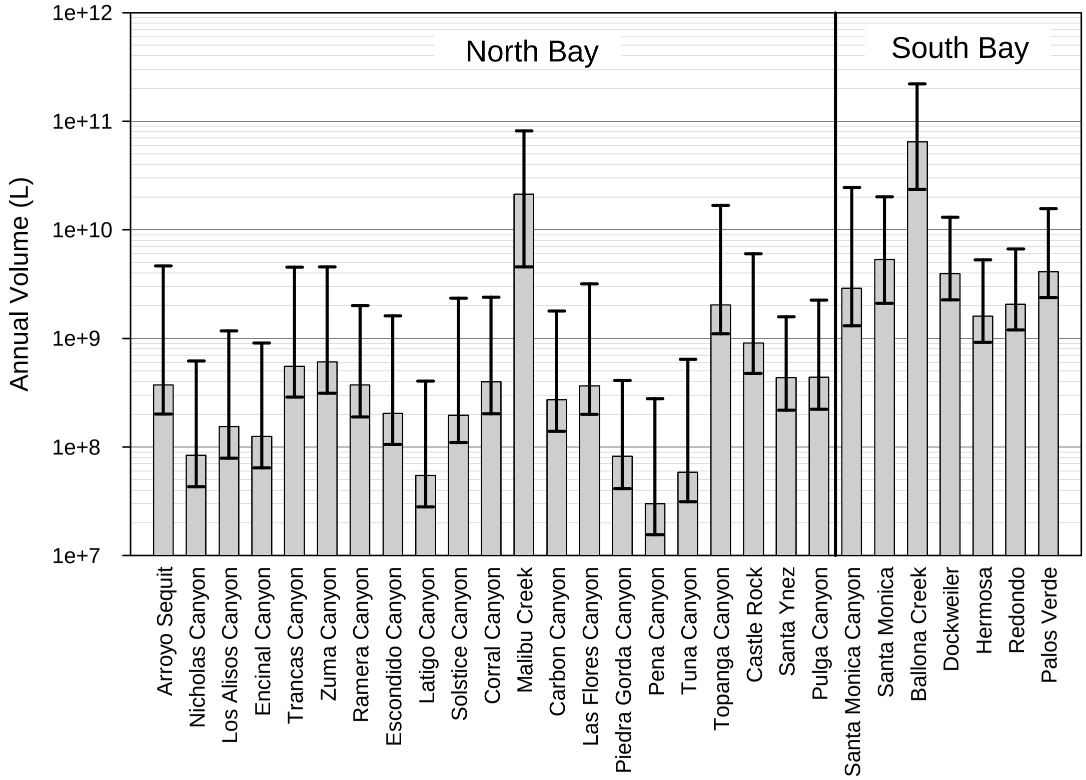


Figure 5. Daily flow duration curves for SMB watersheds.

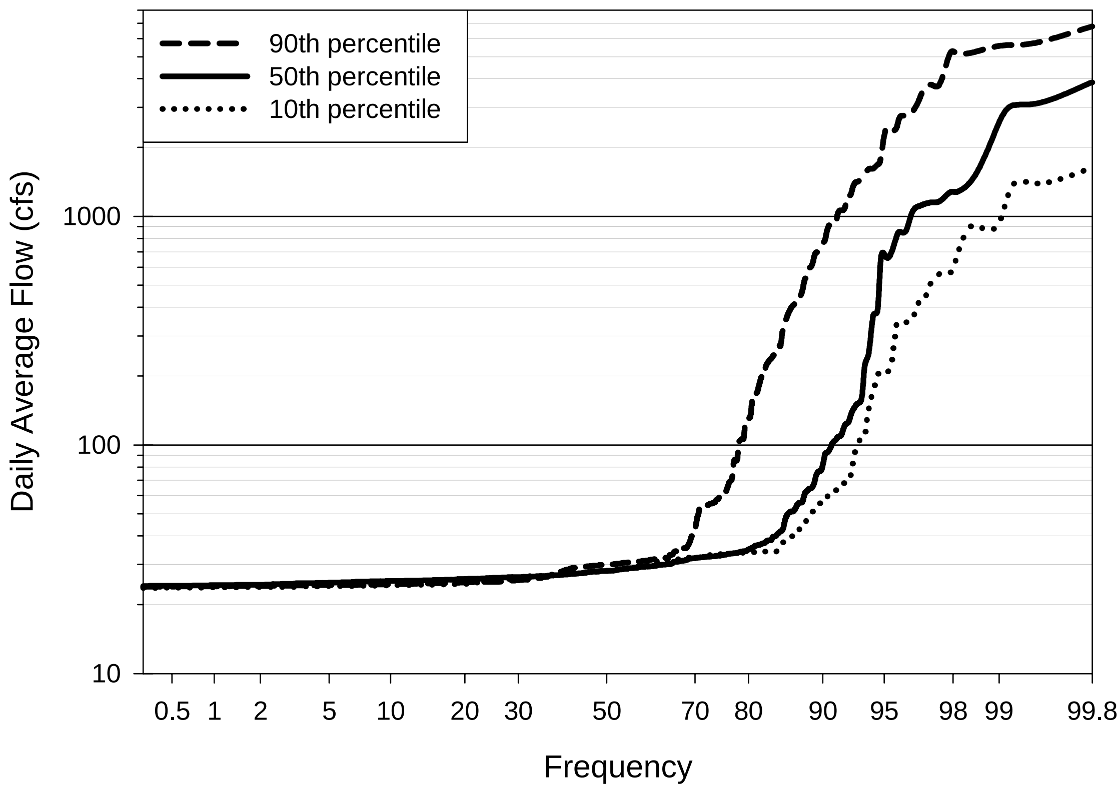


Table 1. Land use aggregation for Santa Monica Bay.

Original Land Use	Aggregated Land Use	Percent Pervious	Original Land Use	Aggregated Land Use	Percent Pervious
Agriculture	Agriculture	94	Mixed Residential	Low Density Residential	60
Communication Facilities	Industrial	25	Mixed Transportation and Utility	Industrial	25
Education	Commercial	15	Mixed Urban	Mixed Urban	50
Floodways and Structures	Open	97	Mobile Homes and Trailer Parks	High Density Residential	40
General Office	Commercial	15	Multiple Family Residential	High Density Residential	40
Golf Courses	Open	97	Natural Resources Extraction	Industrial	25
Harbor Facilities	Industrial	25	Nurseries and Vineyards	Agriculture	94
Heavy Industrial	Industrial	25	Open Space/Recreation	Open	97
High Density Single Family Residential	High Density Residential	40	Other Commercial	Commercial	15
Institutional	Commercial	15	Receiving Waters	Water	100
Light Industrial	Industrial	25	Retail/Commercial	Commercial	15
Light Industrial/Mixed Residential	Agriculture	94	Rural Residential	Open	97
Low Density Single Family Residential	Low Density Residential	60	Transportation	Industrial	25
Maintenance Yards	Industrial	25	Under Construction	Mixed Urban	50
Marina Facilities	Industrial	25	Urban Vacant	Open	97
Military Installations	Commercial	15	Utility Facilities	Industrial	25
Mixed Commercial and Industrial	Mixed Urban	50	Vacant	Open	97

Table 2. Model parameters utilized for modeling of Santa Monica Bay.

Pervious Parameters	Value	
Forest	0.0	%
LZSN	7.0	in
INFILT	0.04	in/hr
LSUR	200	ft
SLSUR	0.03	none
KVARY	3.0	1/in
AGWRC	0.92	1/d
PETMAX	35.0	F
PETMIN	30.0	F
INFEXP	2.0	None
INFILD	2.0	None
DEEPFR	0.40	None
BASETP	0.05	None
AGEWTP	0.05	None
CEPSC	0.10	in
UZSN	0.80	in
NSUR	0.20	Complex
INTFW	1.50	None
IRC	0.70	1/d
LZETP	0.70	None

Impervious Parameters	Value	
LSUR	200	ft
SLSUR	0.030	None
NSUR	0.025	none
RETSC	0.07	in
PETMAX	35.0	F
PETMIN	30.0	F
RETS	0.001	in
SURS	0.001	in