CONCEPT DEVELOPMENT: DESIGN STORM FOR WATER QUALITY IN THE LOS ANGELES REGION

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This project was the first step in exploring the use of a design storm for water quality. This exploration was not undertaken alone, but as part of a Working Group comprised of municipal agencies, consultants, BMP manufacturers, and environmental advocates (Table i-1). The authors are grateful for their participation. This project was partially funded by Los Angeles Regional Water Quality Control Board Agreement 05-314-140-0. The authors wish to acknowledge the modeling contributions of Andi Thayumanvan of Geosyntec.

Table i-1. Members of the Design Storm Working Group

Name	Agency
Vaikko Allen	Contech Stormwater Solutions, Inc.
Steve Carter	Tetra Tech, Inc.
Bill DePoto	Los Angeles County Department of Public Works
Renee DeShazo	Los Angeles Regional Water Quality Control Board
Ken Farsing	City of Signal Hill
Mark Gold	Heal the Bay
Gerry Greene	City of Downey
Kirsten James	Heal the Bay
Shahram Kharaghani	City of Los Angeles
Susan Paulsen	Flow Science Incorporated.
Kristen Ruffel	Los Angeles County Sanitation District
Morad Sedrak	City of Los Angeles
Deb Smith	Los Angeles Regional Water Quality Control Board
Xavier Swammikannu	Los Angeles Regional Water Quality Control Board
Wing Tam	City of Los Angeles
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Abstract

Many waterbodies in the Los Angeles region suffer from impaired water quality. As a result, there are a number of total maximum daily loads (TMDLs) being adopted for urbanized watersheds. These TMDLs establish regulatory requirements to achieve water quality standards. Ultimately, TMDLs stipulate that all wet weather discharges should meet water quality standards regardless of storm size including large, but infrequent events that can result in large-scale flooding. The objectives of this study were to: 1) identify the water quality consequences of managing for different sized storms; and 2) investigate stormwater runoff management strategies to determine their potential effectiveness in achieving water quality targets, and the associated cost, to storms of differing sizes. The objectives were addressed by examining two different conceptual approaches: 1) identifying target runoff volumes or pollutant loads for treatment based solely on rainfall:water quality relationships; and 2) identifying target runoff volumes or pollutant loads for treatment based on effectiveness and cost of treatment technologies.

The first conceptual approach was addressed using Hydrologic Simulation Program-Fortran (HSPF), a watershed-based runoff model. The model was calibrated and validated for Ballona Creek, a highly urbanized watershed at low elevation in the Los Angeles Region. Model results indicated that, for this entire watershed, capturing storms of approximately one-inch precipitation volume would treat 80% of the runoff volume and 80% of the total copper load over a 30-year simulation. Capturing a minimally larger fraction of runoff volume or load would have required capturing significantly larger storm events.

The second conceptual approach was addressed using a modified version of Storm Water Management Model 4.4h (SWMM), a model that simulates long-term hydraulics and pollutant removal for structural best management practices (BMPs). The SWMM was applied to a typical 10-acre high-density residential land use catchment of 42% imperviousness. Three different BMP designs were evaluated using this approach: a swale; a swale with a flow-control basin; and a bioretention basin. At a design storm of 0.75-in rainfall volume or 0.25-in/hr intensity, and assuming a consistent, median level of BMP effectiveness, any of the three BMPs could effectively reduce the average annual frequency of storms that exceeded the dissolved copper water quality standard to less than 5%. Rough cost estimates were applied to each of the three generic BMPs. The bioretention BMP was the most costly for reducing the frequency of exceeding the dissolved copper water quality standard, but was the most cost effective for reducing dissolved copper loads.

The two conceptual approaches examined in this study demonstrated that integrating cost-effective strategies into design standards for determining TMDL implementation policies is possible. However, several technical challenges still exist before design standards for water quality can be incorporated into a regulatory framework including extrapolating to other locations or water quality constituents, further model validation, and assessing confidence in the model to achieve targets. Additionally, policy discussions should include an evaluation of potential implementation strategies such as those for new development/redevelopment versus retrofit applications.

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INTRODUCTION

With a population of approximately 4 million residents and extending across roughly 1,300 km^2, Los Angeles is one of the most populated urban centers in the nation. As a result of this dense population, many of the region's watersheds have been extensively developed leading to increases in watershed imperviousness. Some watersheds, such as Ballona Creek, have an estimated 85% urbanization resulting in over 50% imperviousness.

Unmanaged urbanization and extensive imperviousness lead to increased flow rates and volumes, and decreased water quality. Increased flows arise from decreased infiltration of precipitation. Decreased water quality results from a large number of pollutant sources within the watershed, which is exacerbated when combined with the increased mobilization resulting from imperviousness driven runoff. The combination of increased flows and decreased water quality has resulted in a large number of waterbody impairments. For example, the United States Environmental Protection Agency (USEPA) and the State of California listed 32 different water quality impairments for Ballona Creek in 2003.

Even with the increased flows associated with imperviousness, watershed managers have been very effective at minimizing flood damage associated with storm events. Unlike the historical record, extensive property damage and loss of life rarely occurs in the flood plain regions of Los Angeles. County and City engineers have developed a system of hydrologic planning that efficiently delivers runoff to the ocean through a network of flood control channels. The network is supported through design storm principles that mandate flood control protection from large, but infrequent storm events by predicting runoff volume and timing for each new urban development or redevelopment project.

Despite the relative success of the design storm concept for hydrology, very little work has been conducted to examine design storm principles for water quality. There are many reasons for the lack of design storm principles for water quality including large spatial and temporal variability of runoff concentrations and loads, an incomplete knowledge of the mechanisms and processes that control water quality in stormwater runoff, and insufficient data to create predictable rainfall-water quality relationships. It is clear, however, that existing approaches for controlling water quality in wet weather runoff are inadequate for meeting the regulatory requirement for acceptable water quality. For each impaired waterbody listed by the USEPA and State of California, total maximum daily loads (TMDLs) are required to reduce pollutant inputs and restore beneficial uses. In the case of Ballona Creek, a TMDL has been promulgated for trace metals, including copper, which requires adequate capture and treatment of stormwater runoff to meet water quality standards.

The TMDL in Ballona Creek for metals has one important challenge. The regulatory requirement to meet water quality standards exists for all storms, regardless of size. This requirement to achieve water quality standards must be achieved, while also protecting property from flood damage, maintaining passable roadways, and ensuring public safety. Stakeholders become concerned when water quality and public safety are put at odds, especially when large flood events are relatively rare.

The purpose of this project was to explore design storm concepts for protecting and restoring water quality in the Los Angeles region. The design storm concepts will focus on two primary questions: 1) what size storm needs to be treated in order to meet water quality targets in the receiving water body? and 2) at what size storm should exceedances of water quality targets be forgiven? The motivation for the first question was to optimize storm capture and treatment requirements based on rainfall-runoff relationships. The motivation for the second question was to optimize storm capture and treatment based on best available treatment technology. Answering the first question maximizes water quality relative to build-up and wash-off of pollutants regardless of cost and capability. In contrast, answering the second question maximizes water quality relative to pollutant removal capability and, indirectly, cost. In both cases, the goal is to explore design storm criteria to adequately protect and restore the beneficial uses of our waterbodies, while balancing the technological and financial challenges of treating urban runoff from very large rain events.

METHODS

There are number of different approaches to generating rainfall:runoff relationships. Two primary approaches include empirically based relationships or computer model simulations. The decision to use model simulations for this study was based on three distinct advantages over empirical approaches. First, model simulations enable data estimation from various storm conditions, including dry and wet years, small and large storms, short and long antecedent dry conditions, whereas empirical approaches are limited to just the storms monitored. Second, simulations enable a more accurate picture of the range of runoff concentrations and loads that could be expected. By comparison empirical approaches would have required significant resources to capture an adequately representative number of storm events. Finally, the model selected for simulations of the sample watershed had been previously applied in the Ballona Creek TMDL assessments (LARWQCB 2005), offering a baseline for comparative analysis.

This study was composed of three elements: 1) Summarizing rainfall characteristics; 2) Water quality modeling to assess runoff concentrations from Ballona Creek; and 3) Water quality modeling to assess Best Management Practice (BMP) performance.

Rainfall Characteristics

Long-term rainfall records were used from the gauge at the Los Angeles International Airport (LAX). The LAX has one of the longest records in the region and is located less than four km from the Ballona Creek mouth. Hourly rainfall records were available for the period 1948 to 2004. Rainfall characteristics included quantity, duration, intensity, and antecedent dry period. Independent storms were defined as those with an intervening 6-hr period without rainfall.

Water Quality Modeling to Assess Runoff Concentration

The dynamic hydrologic and water quality model Hydrologic Simulation Program-Fortran (HSPF) was used to simulate runoff volumes and concentrations from Ballona Creek (Bicknell *et al.* 1997). HSPF is a public domain model, supported by the USEPA, capable of simulating the movement of runoff and pollutants from the ground surface, through storm drain and creek networks, and through shallow groundwater to receiving waters. HSPF is widely used, and has been applied in a variety of watershed types and sizes (Donigian *et al.* 1983, Stigall *et al.* 1984), with varying indicators such as flow, sediments, nutrients, bacteria, and metals (Ng and Marsalek 1989, Brun and Band 2000), to predict a large variety of management endpoints (Moore *et al.* 1992, Chew *et al.* 1991).

This study used HSPF to model flow, total suspended solids (TSS), and total copper at short (15 minute) time steps. The modeling effort builds upon a previous hydrologic validation (Ackerman *et al*. 2005) and a water quality calibration and validation at both land use and watershed scales. For hydrologic parameterization, a decadal simulation (WY1990-1999) was conducted with the first five years for calibration and the second five years for validation (Figure 1). The water quality component was developed by calibrating land use runoff water quality at small single land use catchments using multiple samples collected throughout more than two dozen storm events. The land use model parameters were then validated by predicting water quality at the mouth of Ballona Creek. Of the seven storms at the mouth of Ballona Creek used as validation data, simulated total copper event mean concentrations (EMCs) averaged within 11% of measured concentrations; simulated total copper loads were within 6% of measured loads.

Water Quality Modeling to Assess BMP Performance

The Stormwater Management Model (SWMM) version 4.4h was used to assess BMP performance. SWMM is a public domain model, supported by the USEPA, capable of simulating the movement of runoff and pollutants from the ground surface, through pipes/channel networks and storage/treatment facilities, and finally to receiving waters. SWMM version 4.4h is divided into several modules, or Blocks, including Rain, Runoff, Transport, Storage/Treatment (S/T), Extran, Statistics, and Combine. For this effort, only the S/T and Statistics Block were used. The S/T Block has the capability of modeling long-term, continuous hydraulic and water quality treatment processes in either detention or non-detention units (e.g., detention basins or swales, respectively). Several BMP design variations and hydraulic structures, such as flow splitters, weirs, perforated risers, orifices, or custom outlet structures may all be modeled in the S/T Block. The Statistics Block provides summary statistics for model output from any of the other blocks. Detailed descriptions of these and the other SWMM modules are available in Huber and Dickinson (1988), James (2000a, 2000b), and at http://ccee.oregonstate.edu/swmm/.

The calibrated HSPF model was used to produce 30 years of hourly hydrographs and total copper pollutographs for a hypothetical 10-acre high-density residential (HDR) catchment near the LAX rain gauge. HDR was defined according to Southern California Association of Governments (SCAG; 2001). The runoff modeling assumed 42% imperviousness in the HDR catchment. The total copper pollutographs were translated to dissolved copper pollutographs by assuming a fixed dissolved percentage of 55% of the total concentration. This value is based on land use storm event monitored at an HDR site by the Los Angeles County Department of Public Works (LADPW 2000, 2001) and is consistent with storm event pollutograph data from Ballona Creek collected by the Southern California Coastal Water Research Project on March 28, 2006 (SCCWRP unpublished data).

The runoff simulation output from HSPF was routed to the S/T Block of SWMM, which was then used to evaluate the water quality benefits achieved by BMPs placed at the catchment outlet. The three biofilter BMP types evaluated were: 1) a vegetated swale; 2) a flow-controlled swale (equalization basin upstream of a swale); and 3) a bioretention basin. For each of these BMP types, the performance was evaluated over a range of unit design sizes (normalized by impervious catchment area). Overall performance of these BMPs was based on three factors: 1) the fraction of stormwater runoff receiving treatment (often referred to as percent of runoff captured, or simply percent capture); 2) the volume loss due to infiltration; and 3) the achievable effluent concentration.

BMP performance measures

Percent capture for flow through BMPs was calculated as the ratio of net inflow volume to the BMP to the total catchment runoff volume. Percent capture for detention based BMPs was calculated as the ratio of runoff that passes through the outlet structure to the total runoff volume.

All BMPs were evaluated as off-line BMPs, such that the bypass occurred once the design volume or design flow rate was exceeded.

The volume reduction achieved by a BMP was a function of the capture efficiency and the fraction of captured stormwater runoff that was infiltrated, evaporated, or transpired by vegetation. The International BMP Database has shown that as much as 35% to 40% of stormwater volume in biofilters can be lost to infiltration (Strecker *et al.* 2004), which indicated that this may be an important mechanism that should be included in the water quality analysis. A conservative infiltration rate of 0.15 in/hr due to percolation into native soils was assumed for all BMP simulations. This value is typical of a hydrologic soil group B/C type soil (James and James 2000a). SWMM results showed a long-term average volume reduction of 15% to 22% in the simulated swales based on this assumption.

Pollutants were routed through the BMPs as plug-flow and pollutant removal was evaluated at each time step through the use of the following removal equation:

$$R = 1 - \left[\frac{Effluent\ Concentration}{Influent\ Concentration} \right] \quad (1)$$

BMP water quality performance was based on the American Society of Civil Engineers (ASCE) International Stormwater BMP Database (www.bmpdatabase.org). The ASCE BMP database is comprised of carefully examined data from a peer-reviewed collection of studies that have monitored the effectiveness of a variety of BMPs in treating water quality pollutants from a variety of land use types. Analyses of BMP performance data contained in the database suggested that effluent quality rather than percent removal is a much more accurate and reliable prediction of performance in modeling stormwater treatment (Strecker *et al*. 2001). As such, the effluent concentration approach was used for this analysis. If the influent concentration at any simulation time step was estimated to be less the BMP effluent, no treatment was assumed. For this study, the median biofilter effluent concentration of 6 μg/L dissolved copper from the BMP Database summary report was used (GSC and WWE 2006) for all BMP types. The effluent concentration of 6 μg/L dissolved copper arose from 37 different BMP installations with an upper and lower 95% confidence interval about the effluent median of 5 and 7 μg/L dissolved copper, respectively. The range of effluent median concentrations across all BMP types ranged from 5 to 10 μg/L dissolved copper.

The California Toxics Rule (CTR) criterion for dissolved copper with an assumed hardness of 100 mg/L was used as the water quality benchmark for evaluating BMP performance. This hardness value was deemed appropriate since recently collected monitoring data for Ballona Creek (LADPW 2001, 2002, 2003, 2004, 2006), indicated that the observed wet weather hardness ranges between 32 and 530 mg/L as $CaCO_3$, with a median value of 110 mg/L as $CaCO_3$. Sensitivity analysis was performed to test the effect of altering the water quality criterion based on variations in hardness. Comparisons of BMP treatment effectiveness were recalculated based on the 25th and 75th percentile of hardness values measured by LADPW (2001, 2002, 2003, 2004, 2006).

The Statistics Block of SWMM was used to divide the runoff and concentration time series into discrete storm events, which were defined as periods of runoff with a minimum interevent time of 6 h. For each storm event, the EMC was calculated and compared to the CTR water quality benchmark. The average annual percent exceedance (i.e., number of benchmark exceedances divided by the total number of storms) was then calculated for each BMP type and size. Sensitivity analysis was conducted for assessing variability in inter-event time.

BMP selection and design

The simulation and cost analyses of the three biofilter BMP types required assumptions with regard to their specific design parameters. Conceptual illustrations of the three BMP types are included in Figure 2. For the vegetated swale simulation, a flow-splitter is assumed to control the rate at which flows enter the swale such that any flow rate greater than the max flow are bypassed and untreated. For the flow-controlled swale, the equalization basin controls the flow rate to the swale such that bypass will occur if the volume of the basin is exceeded. For the bioretention basin, the infiltration into the amended bioretention soils controls the flow rate such that bypass will occur if the storage volume of the bioretention basin is exceeded. The following paragraphs briefly describe the major design assumptions for each simulated BMP type.

<u>Vegetated Swale</u>: For the vegetated swale simulations, several design flow rates were evaluated. Side slopes were assumed to be 3:1 and longitudinal slopes were assumed to be 2%. A Manning's roughness coefficient of 0.25 was applied and the final dimensions were determined for each design flow rate based on a 10-min minimum residence time in the swale. Infiltration into native soils was modeled at 0.15 in/hr. A freeboard of 1 ft was also assumed for costing purposes.

<u>Flow-Controlled Swale</u>: For the flow-controlled swale simulations, several unit design volumes for the equalization basin were evaluated with the swale sized according to the maximum discharge rate from the basin. For all simulations, a 6-h drain time was assumed. No volume losses or treatment was assumed for the basin. All other swale sizing assumptions were applied.

<u>Bioretention Basin</u>: For the bioretention basin simulations, several unit design volumes were evaluated. All designs were assumed to have an 18-in ponding depth with 2 ft of amended soils having a saturated hydraulic conductivity of 1.8 in/hr overlaying a perforated underdrain outlet. Similar to the swale simulations, infiltration into native soils beneath the underdrain was modeled at 0.15 in/hr.

Cost analysis to assess BMP effectiveness

Capital and maintenance costs for the three BMP types were evaluated for the design sizes that were estimated to achieve 5%, 10%, and 20% exceedance of the dissolved copper benchmark for the hypothetical 10-acre HDR catchment. The BMP design sizes used for this cost analysis are provided in Table 1. The dimensions of the BMPs were estimated using the design assumptions described above. The estimated footprint areas for each BMP type are shown in Table 2.

Capital costs were estimated primarily based on unit regional costs from RSMeans Cost Data. The estimates include site preparation (e.g., clearing, grubbing, erosion control), earth works (e.g., excavation, grading, hauling, backfilling), and miscellaneous appurtenances, such as catch basin inlets, geotextiles, perforated underdrains, outlet structures, and culverts. The estimates do not include design engineering, permitting, project management, construction management, engineering during construction, or incidental costs associated with existing infrastructure conflicts (e.g., utilities).

Operation and maintenance costs were estimated from Muthukrishnan *et. al.* (2004), Lampe *et. al.* (2005), and Bannerman *et al*. (2003). Capital and Operation/maintenance (O&M) costs were adjusted using the consumer price index (CPI) for Los Angeles in May 2007. Land costs were estimated to be $1M to $3M/acre based on estimates from certified real estate brokers and City Engineer and Planning staff. Because of extreme price variations, land costs do not include existing structures, condemnation, relocation, and demolition. The pricing for land costs are presented separately in the analysis so updated information can be used, if desired.

RESULTS

Rainfall, Flow, and Water Quality

Storm event rainfall depth ranged from 0.01 (minimum gage reading) to nearly 7.44 in at the LAX gage for the 56-year period from 1948 to 2004 (Figure 3). Median storm depth was 0.17 in and the 80th percentile was 0.66 in. Storm averaged rainfall intensity ranged from 0.01 (minimum gage reading) to 1.57 in/hr. Median rainfall intensity was 0.04 in/hr and the 80th percentile was 0.11 in/hr. Rainfall duration ranged from <1 to 101 h. Median rainfall duration was 5 hrs and the 80th percentile was 13 hrs. Antecedent rainfall between storms ranged from 0.3 d to 226 d. Median antecedent dry period was 3 d and the 80th percentile was 15 d.

Mean daily flow at Ballona Creek ranged from 0.05 m^3/s to 200 m^3/s during the 30-yr period WY 1970 to 1999 (Figure 4). This time period included the driest year, the wettest year, and the median year in the 30-year record at this site. The break between low, dry weather flow and high, wet weather flow occurred around 2 m^3/s. Dry weather flows occurred during roughly 93% of the time during the 30-year record.

Thirty-year model simulations for Ballona Creek defined the relationship between increased precipitation volume and increased runoff volume (Figure 5). Approximately 66% of the cumulative runoff volume occurred during storms of 0.75 in or less. In an especially dry year, approximately 90% of the cumulative annual runoff volume occurred during rainfall events of 0.75 in or less. In contrast, approximately 55% of the cumulative annual runoff volume in an especially wet year occurred during rainfall events of 0.75 in or less.

Thirty-year model simulations for Ballona Creek defined the relationship between increased precipitation volume and increased mass emissions of total copper (Figure 6). Between 60% and 73% of the cumulative annual runoff pollutant loads occurred during storms of 0.75 in. or less. In an especially dry year, approximately 90% of the cumulative annual runoff load occurred during rainfall events of 0.75 in or less. In contrast, approximately 59% of the cumulative annual runoff load in an especially wet year occurred during rainfall events of 0.75 in or less.

While there was a profound relationship between rainfall volume and runoff volume or total copper load, thirty-year model simulations for Ballona Creek indicated that there was only a moderate relationship between total rainfall volume and total copper event mean concentrations (Figure 7). This highly variable relationship reflects differences in rainfall intensities, rainfall location within the catchment, antecedent dry periods, rainfall durations, and other potential factors. In fact, at 0.75 in rainfall volume, model simulations of individual storms predicted total copper EMCs between 60 and 140 μg/L.

BMP Performance

The BMPs evaluated were flow-through (swale) or volume-capture (bioretention) type devices, and the performance evaluation for each varied. For instance, swales were evaluated based on capturing flow, hence rainfall intensity was the storm characteristic of greatest interest. In contrast, bioretention devices were evaluated based on capturing volume, hence rainfall quantity was the storm characteristic of greatest interest. The flow-controlled swale, which has both retention and flow-through design elements, was evaluated on both rainfall intensity and quantity.

Swale

The volume treated by the swale was a function of BMP sizing (Figure 8). Approximately 49% of the average annual runoff volume from the modeled HDR catchment would be treated at a median rainfall intensity of 0.04 in/hr, the median intensity at the LAX rain gauge. Capturing 0.2 in/hr would result in treating 90% of the average annual runoff volume from the modeled catchment.

The reduction in dissolved copper loads also varied as a function of BMP sizing (Figure 8). Approximately 32% of the average annual dissolved copper load would be removed by the swale if it were sized to capture storms with 0.04 in/hr intensity. Capturing 0.2 in/hr intensity would result in average annual load reductions of 68% from the modeled catchment.

On average, approximately 50% of the storms per year would exceed the dissolved copper water quality standard of 13.4 ug/L from our modeled catchment (Figure 8) without BMPs. A swale sized to capture an intensity of 0.04 in/hr would reduce the average exceedence rate to 32% of the storms per year. Capturing a 0.2 in/hr event would reduce the average exceedence rate to 7% of the storms per year.

Flow-controlled swale

The volume captured by the flow-controlled swale was a function of BMP sizing (Figure 9). Approximately 52% of the average annual runoff volume from the modeled HDR catchment would be captured using a rainfall volume of 0.17 in, the median rainfall volume at the LAX gauge. Capturing 0.75 in would result in treating 97% of the average annual runoff volume from the modeled catchment.

The reduction in dissolved copper loads also varied as a function of BMP sizing (Figure 9). Approximately 40% of the average annual dissolved copper load would be removed by the swale if it were sized to capture storms with 0.17 in rainfall volume. Capturing 0.75-in volume storm events would result in average annual load reductions of 83% from the modeled catchment.

On average, approximately 50% of the storms per year would exceed the dissolved copper water quality standard of 13.4 µg/L from our modeled catchment without BMPs (Figure 9). A flow-controlled swale sized to capture a rainfall volume of 0.17 in would reduce the average exceedence rate to 21% of the storms per year. Capturing a 0.75 in event would reduce the average exceedence rate to 7% of the storms per year.

Bioretention

The volume captured by the bioretention BMP was a function of BMP sizing (Figure 10). Approximately 50% of the average annual runoff volume from the modeled HDR catchment would be captured using a rainfall volume of 0.17 in, the median rainfall volume at the LAX gauge. Capturing 0.75 in would result in treating 92% of the average annual runoff volume from the modeled catchment.

The reduction in dissolved copper loads also varied as a function of BMP sizing (Figure 10). Approximately 50% of the average annual dissolved copper load would be removed by the swale if it were sized to capture storms with 0.17 in rainfall volume. Capturing 0.75-in volume storm events would result in average annual load reductions of 94% from the modeled catchment.

On average, approximately 50% of the storms per year would exceed the dissolved copper water quality standard of 13.4 ug/L from our modeled catchment (Figure 10). A bioretention BMP sized to capture 0.17 in would reduce the average exceedence rate to 30% of the storms per year. Capturing a 0.75-in event would reduce the average exceedence rate to 5% of the storms per year.

Sensitivity Analysis

The effectiveness of a BMP varied as the definition of what constituted a storm changed (Figure 11). In this case, inter-event times of 6 hr resulted in 50% of the storms from our HDR catchment exceeding the copper water quality standard of 13.4 µg/L. If, however, the inter-event time was altered to 24 hr, then 70% of the storms per year would exceed the copper water quality standard. In magnitude, this equates to roughly 9.5 storms per year for the 24-hr interevent time compared to 11 storms per year for the 6-hr interevent time. An assessment of treatment efficiency also changes. For example, using a flow controlled swale designed for a 0.75-in storm, roughly 3% of the storms would be expected to exceed the copper water quality standard regardless of interevent time. However, this is an average of 0.5 storms per year for the 6-hr interevent time compared to an average 1 storm per year for the 24-hr inter-event time.

The effectiveness of a BMP also varies as the definition of what constitutes the water quality standard (Figure 12). In the case of dissolved copper, the water quality standard varies as a function of hardness. Based on the 25th and 75th percentile distributions of hardness from Ballona Creek, the water quality standard for copper could range from 8.3 to 21.5 µg/L copper. As a result, the exceedence frequencies also change. Assuming the lower hardness value, roughly 61% of the storms from our modeled catchment would exceed water quality standards without treatment. In contrast, assuming the higher hardness value, roughly 36% of the storms from our modeled catchment would exceed water quality standards without treatment. The relative BMP performance between low and high hardness values is amplified at smaller design sizes than larger design sizes. For example, the frequency of water quality standard exceedences at BMP design sizes of 0.17 in rainfall is 15% versus 30% depending upon hardness. At 0.75 in design sizes, however, the frequency of exceedence at lower and higher hardness values results was about the same (3%).

Comparison Among BMPs

The design criteria for each of the three targeted BMPs were selected based on specified exceedence frequencies of 20%, 10% or 5% (Table 1). The swale BMP would need to be designed to capture rainfall intensities of 0.08 to 0.25 in/hr to meet the required exceedence frequencies. The bioretention BMP would need to be designed to capture rainfall volumes of 0.26 to 0.70 in rainfall volume to meet the required exceedence frequencies. The flow-controlled swale required a smaller rainfall intensity than the swale only BMP to achieve similar exceedence frequencies. The flow-controlled swale also required a smaller rainfall volume than the bioretention BMP. However, the flow-controlled swale requires both a runoff detention basin and a flow through system to work effectively.

Although the three BMPs may be sized to meet similar exceedence frequencies, the load removal efficiency was not necessary similar (Figure 13). The BMP model estimated that the swale and flow-controlled swale had similar load removal efficiencies. For example, when the two BMPs were sized to achieve a 20% exceedence frequency, both BMPs also removed approximately 40% of the average annual dissolved copper load. In contrast, the bioretention BMP, if sized to achieve a 20% exceedence frequency, would result in a 64% average load reduction. A similar disparity in load reduction efficiency among the three BMPs was also observed at the 10% and 5% exceedence frequency design standards. The difference was primarily due to increased infiltration volumes during surface ponding that occurs in bioretention BMPs as compared to infiltration as water flows through the swales. Surface ponding provides more time for infiltration than does continuous flow-through. No volume losses were modeled in the equalization basin.

Cost Analysis

The first year cost estimates for the three BMPs ranged from $162,000 to $802,000 depending on BMP type and size for the 10-acre catchment (Table 3). By far, land costs were the dominant factor influencing total cost of all the BMPs regardless of size. Land costs accounted for 85% to 92% of the total first year costs. Without land purchase, the first year cost estimates for the three BMPs ranged from $13,000 to $115,000. The bioretention BMP had the greatest land requirements of the three BMPs evaluated (Figure 14).

In general, the bioretention BMP was the most expensive of the three BMPs modeled (Table 3). The cost differential increased as the size of the BMPs increased (i.e., from 20% to 5% exceedence frequencies). The swale was the least expensive of the three BMPs modeled. When sized for 20% exceedence frequencies, the swale BMP was roughly half the cost of the bioretention BMP. When sized for the 5% exceedence frequency, the swale BMP was roughly two-thirds the cost of the bioretention BMP.

While the bioretention BMP was the most expensive BMP relative to exceedence frequencies, the bioretention BMP was the most cost-effective BMP for load removal (Figure 15). For example, at a first year cost estimate of $200,000, the bioretention BMP removed approximately 65% of the annual average copper load. In contrast, the swale and flow-controlled swale removed only 55% and 35% of the average annual copper load, respectively, for the same cost.

DISCUSSION

The results from this study indicated that there was a strong relationship between water quality and rainfall characteristics such as precipitation volume or intensity. These relationships appeared to be relatively predictable for hydrology and total copper loading. The relationships between rainfall characteristics and copper concentrations were less predictable, but sufficiently understood that estimates of EMCs could be modeled.

Rainfall:runoff relationships indicated that there was an efficiency that can be achieved in reducing runoff volume or total copper loads. Approximately 80% of the runoff volume and copper load over a 30-year period from Ballona Creek could be captured if storms up to roughly one inch could be treated. Capturing 90% of the decadal runoff volume and copper load from Ballona Creek, however, would require a BMP nearly triple the size of a 1-in storm. Thus, a small increase in volume capture would require dramatically large increases in BMP sizes.

High-density residential land uses were utilized for BMP modeling. This land use was elected because HDR represented a large fraction of the Ballona Creek watershed (Dojiri *et al*. 2003). In addition, the water quality from the Ballona Creek watershed was similar to the water quality observed from HDR runoff. In fact, Park and Stenstrom (2006) indicated that HDR was one of the land uses with the greatest leverage for making changes in copper loads from the Ballona Creek watershed.

Three different BMPs were modeled to address effectiveness and efficiency of technology to improve water quality. The modeling results indicated that bioretention based BMPs were the most expensive relative to reducing exceedence frequencies of the copper water quality standard. However, bioretention BMPs were the most cost-effective for reducing copper loads. Swales, which turn out to be the cheapest alternative for reducing exceedence frequencies, are the least cost-effective for reducing loads. Therefore, watershed managers will need to carefully examine their true objectives with regards to water concentrations or loads prior to selecting the preferred BMP and developing design standards.

There were at least three significant assumptions required to complete this study. The first assumption was applying a ratio of dissolved copper relative to total copper in stormwater runoff. Modeling exercises to date have consistently used total copper (Ackerman *et al*. 2005). Models that focus on total copper are fairly robust and have known levels of accuracy, precision, and bias. Total copper was also modeled because a substantial database of total copper exists for Ballona Creek. In contrast, relatively little dissolved copper data exists and models of dissolved copper do not exist for the Ballona Creek watershed or any other watershed in southern California. However, the benchmarks for water quality are expressed as dissolved copper, which necessitated the total to dissolved translation. A multiplier of 55% dissolved copper was used for this study based on nearly 40 storm samples from a high density residential land use in Los Angeles County (LACDPW 2000, 2001). This relative fraction was consistent with results from a single storm pollutograph at Ballona Creek collected by SCCWRP, but is higher than the relative dissolved fraction in storm samples collected at Ballona Creek by LACDPW (2006). In addition, based on the sensitivity analysis from the present study, hardness should be simultaneously modeled to ascertain accurate water quality standards on a storm-by-storm basis.

The second significant assumption used in this study that deserves additional investigation is the use of a constant BMP effluent quality concentration. Dynamically modeled (1-hr time steps) flow and water quality data were used as input parameters for the BMP simulation. Ideally, one would want to dynamically model BMP performance as well. However, modeling BMP mechanisms and processes are rare in the literature due to the difficulty in parameterizing the many known physical, chemical, and biological processes that affect fate and transport of urban pollutants (Ackerman et. al., *in press*). Instead, static effluent quality based on the national database of BMPs (GSC and WWW 2006) was used to predict potential outcomes. While this is a robust dataset for some of the BMPs selected herein, it is not complete and includes many locations besides southern California. However, large regional differences in effluent quality from BMPs have not been detected (Strecker *et al*. 2004).

The third assumption used in this study was how BMPs were designed. Using generically designed BMPs was a necessity for the present study, but generic designs are rarely applicable in the real world. There are a large number of site-specific factors that need to be addressed in the design, and cost, of a BMP. For example, infiltration was not applied to the equalization basin upstream of the swale, but certainly some infiltration could occur and could even be added to the design of this BMP to enhance performance. As a result of this and other factors, the effectiveness of these BMPs may be underestimated. In fact, the number of potential design factors is as numerous as the number of locations BMPs could be installed. Therefore, this study did not attempt to explain all possible BMP scenarios, but merely some generic examples for use in evaluation of potential design storms.

Technical Issues Associated With Implementing Design Storm Standards

There are a large number of technical issues associated with implementing design storm standards. Three are summarized here as direct outgrowths of this concept study. The first issue addresses how to extrapolate the concepts developed in the Ballona Creek watershed to other watersheds. There are a multitude of factors that will influence BMP design in and around Los Angeles County. The most obvious is changes in rainfall characteristics. While we examined long term rainfall on the coastal plain at LAX where long term average median rainfall was roughly 0.5 in, it can be much greater in other areas of the county such as the valleys (median rainfall is approximately 1.0 in at gauge 210 near Burbank) or the mountains (median rainfall is approximately 1.75 in at gauge 425 near San Gabriel Dam). Another obvious extrapolation issue is applicability to different land use types. The contributions of flow, volume, and water quality from varying land uses can vary significantly. In cases where there are fewer pollutant sources and less imperviousness, copper concentrations and loads could be substantially reduced indicating the need for lesser design storm standards. Of course, the opposite may be true for land uses with greater sources and/or imperviousness. The last obvious extrapolation issue is associated with other constituents that do not behave like total copper. One example is fecal indicator bacteria that not only have different rainfall:water quality relationships than copper, but may require different types of BMPs to ameliorate excessive concentrations and loads. Therefore, caution is advised if the design storm standards for one constituent are applied to other constituents of concern.

The second technical issue associated with implementing design storm standards is our confidence to model copper. Once again, there are several obvious places that need to be evaluated. Two of these are explicitly stated assumptions in the model; the constant ratio of dissolved to particulate copper and static BMP effluent concentration. There is little reason to believe that either of these assumptions is accurate on short (i.e., within storm) time scales. Based on empirical data averaged over multi-storm time scales, however, these assumptions may be valid and is the basis for our approach evaluating EMCs and long-term annual average exceedence rates. Developing and implementing design storm standards must be conscious of these time scale issues since our confidence in the model to simulate long-term averages is greater than short-term instantaneous time scales. One technique modelers use to assess confidence is to explicitly model variability using stochastic approaches (e.g., Monte Carlo simulation). Modeling variability could then be used to evaluate the likelihood of achieving design storm standards at various time scales.

The third issue associated with implementing design storm standards is feasibility, which interweaves both technological and policy issues at the watershed scale. The primary policy feature of this issue is cost. The primary technological feature is implementing design storm BMPs in new development or redevelopment applications versus retrofit of existing development. The cost analysis used for this study was designed as a tool to compare the cost efficiency of different BMPs and not as an implementation feasibility exercise. However, it was clear that different BMPs had varying cost structures and that flexibility was key to cost optimization. For example, land costs always represented the largest proportion (up to 90%) of the BMP cost estimates. When public or open land is available, such as in a new development or redevelopment application, flexibility is enhanced and BMP implementation costs would be much less expensive. In a retrofit scenario where public or open land is less available, there are typically large constraints on BMP design alternatives and costs would correspondingly increase, especially if private land and associated structures need to be purchased. If these costs become prohibitively expensive, different implementation options could be explored. Some implementation options might include differential design storm standards for new development or redevelopment versus retrofit. Alternatively, implementation options might be considered such as watershed pollutant trading, where BMPs can be enhanced in new/redevelopment areas, or scaled back in retrofit areas, as needed.

CONCLUSIONS

- **BMP modeling appears to be an acceptable conceptual approach for setting design storm standards**

  There are multiple conceptual approaches for setting design storm standards. We examined two in this study. The first was watershed-scale modeling that focused on potential efficiencies in rainfall:water quality relationships regardless of capability to capture and treat runoff discharges. The second was catchment-scale BMP modeling that incorporated technology based approaches for capturing and treating runoff discharges. The two approaches generated similar rainfall volume or intensity targets, but the BMP modeling provided additional metrics that many stakeholders found useful. These factors provided pollutant reduction frameworks including BMP design options, sizing criteria, and cost estimates.

- **The frequency of water quality criteria exceedences and pollutant load reduction both need to be addressed when choosing design storm standards**

  The various BMPs examined in this study had differential performance capabilities. For example, swales appeared to be the most cost effective BMP for reducing exceedence frequencies of the dissolved copper water quality criterion, but the least cost effective for copper load reductions. In contrast, bioretention BMPs were the most cost effective for copper load reduction, but the least cost effective for reducing dissolved copper exceedence frequencies. This was logical because the bioretention BMP has added treatment via enhanced volume losses (i.e., increased infiltration through ponding) that the swale did not. However, the added treatment for bioretention requires more design components and land area so it comes at a greater cost.

- **The size of a BMP is only one of many factors affecting performance**

  This study examined potential BMP performance largely as a function of size, but there are many other factors than can also control BMP performance. Many are within the control of the practitioner such as design options for treatment (e.g., flow routing, infiltration, active treatment, treatment trains, media types, outlet configurations, etc.). There were also several factors that were not within the control of the practitioner including site-specific construction constraints (e.g., availability of land, geological setting for infiltration, etc.). This study concluded that simple, generic, well-designed approaches were likely the best conceptual approach to modeling because of their ability to be extrapolated to many locations. This also leaves greater flexibility to enhance site-specific applications where uncontrollable constraints become problematic.

- **There are a number of factors for setting design storm standards that are not technical, but political**

  There needs to be a strong scientific foundation in any standard setting process, but some decisions ultimately are policy decisions and are affected by the will of the community at large. For example, BMP modeling scenarios were based on design storm standards of 5%, 10%, or 20% average annual frequencies of exceeding the copper water quality criterion. This roughly equates to <1, 1.5, or 3 storms annually for an average year of 15 storms. While a tremendous amount of technical knowledge is required for designing and modeling the BMP, the selection of an allowable exceedance frequency (i.e., 5%, 10%, or 20%) is not a scientific decision alone.

RECOMMENDATIONS

Before design storm criteria can be incorporated into a regulatory framework, the application of the technical concepts developed herein need to be evaluated in greater detail. The following represents a partial list of questions that should be addressed in achieving these criteria:

- **Can the design storm concepts developed herein be extrapolated to other watersheds?**

  In order to create design storm criteria, the concepts developed and tested in this study need to be extrapolated to other locations in the Los Angeles region. This is important because rainfall volume and intensity can double or triple from the coastal plain to the foothills and mountainous regions. Therefore, the rainfall:water quality relationships should be explored using other rain gauges and in other watersheds. Another important extrapolation would be to model BMP effectiveness and efficiency at other land uses besides high density residential. Finally, the rainfall:water quality relationships and BMP modeling should be evaluated for other constituents.

- **How confident are we in our ability to model design storm targets?**

  One limitation of the current study was the ability to accurately model BMP performance. Issues such as dissolved versus particulate copper concentrations in runoff, copper content on particles of various sizes, and particle size distributions all affect runoff concentrations and BMP performance. Dedicated data collection to address each of these issues will dramatically improve the ability to simulate BMP performance and effluent quality. Even then, watershed and BMP modeling are imperfect. Therefore, improved estimates of variance are recommended in order to assess the probability of achieving water quality exceedence frequencies or load reduction targets. This could be accomplished using Monte Carlo based statistical techniques. Monte Carlo techniques are one method to overcome the current reliance on central tendencies of concentration such as medians and event mean concentrations.

- **How can a design storm standard be implemented across an entire watershed?**

  Once design storm criteria are developed, an implementation strategy should be in place to ensure successful application. Significant consideration should be given to standards for new development or redevelopment compared to retrofit applications. The differences lie in the flexibility to adapt and implement a variety of BMP designs. In new development/redevelopment situations, BMP designs and applications are less limited and can be implemented with the greatest cost-effectiveness. In retrofit applications, however, the options for BMP design and application are reduced due to the constraints of existing infrastructure and land availability. As a result, costs correspondingly increase. This may lead to differential applications of design storm criteria throughout a watershed that the regulatory framework may need to consider.

Figure 1. HSPF calibration and validation at Ballona Creek (WY 1990-1999) from Ackerman et al. (2005).

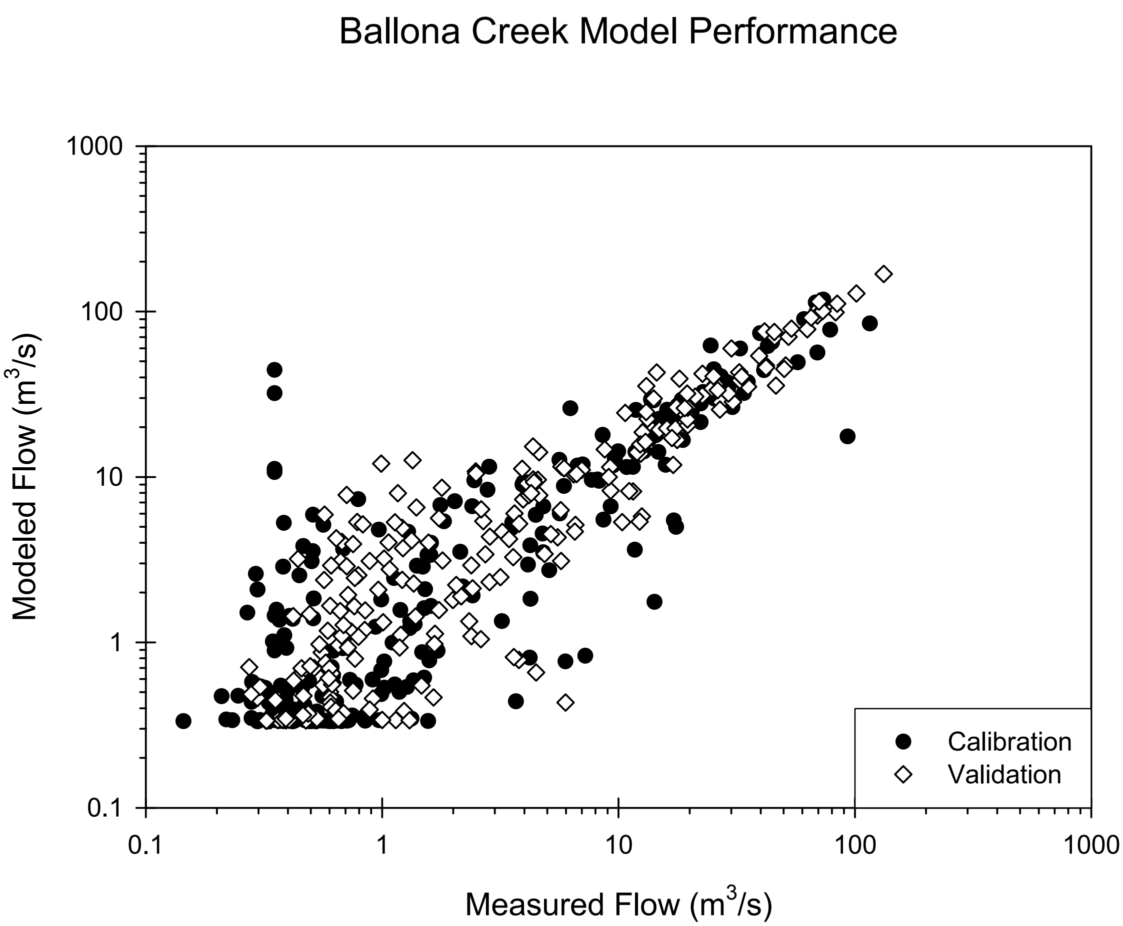


Figure 2A. Schematic plan and profile views of the Swale BMP selected for evaluation.

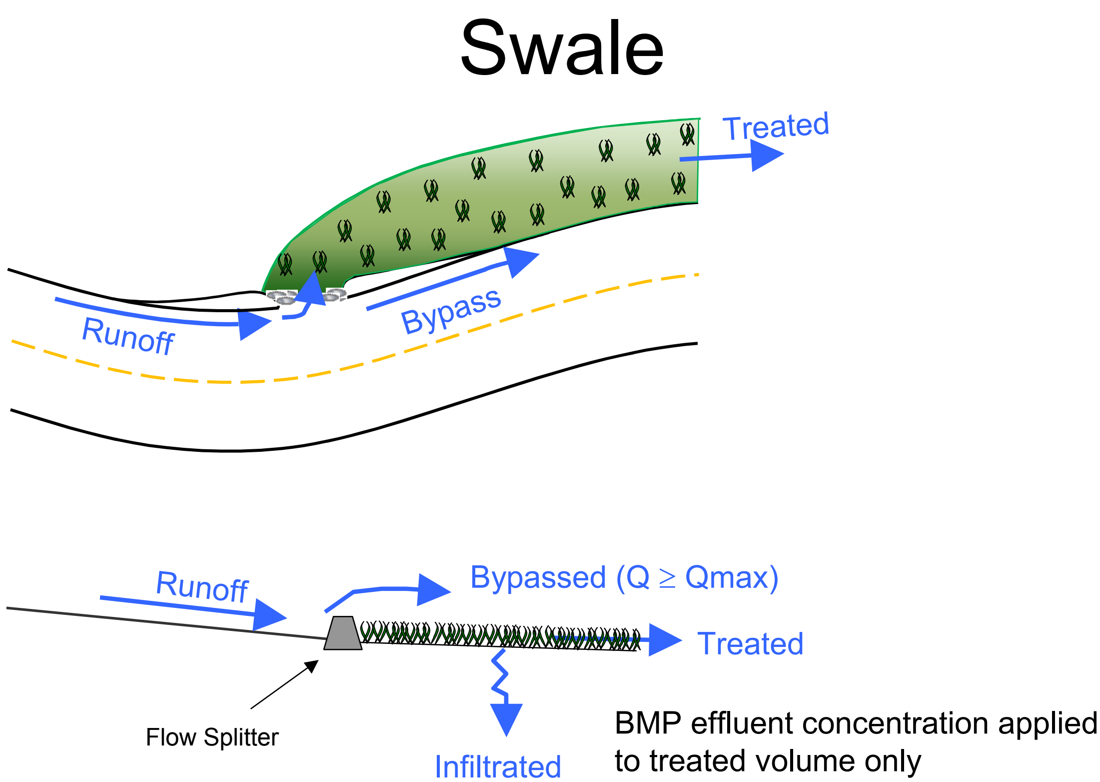


Figure 2B. Schematic plan and profile views of the Flow Controlled Swale BMP selected for evaluation.

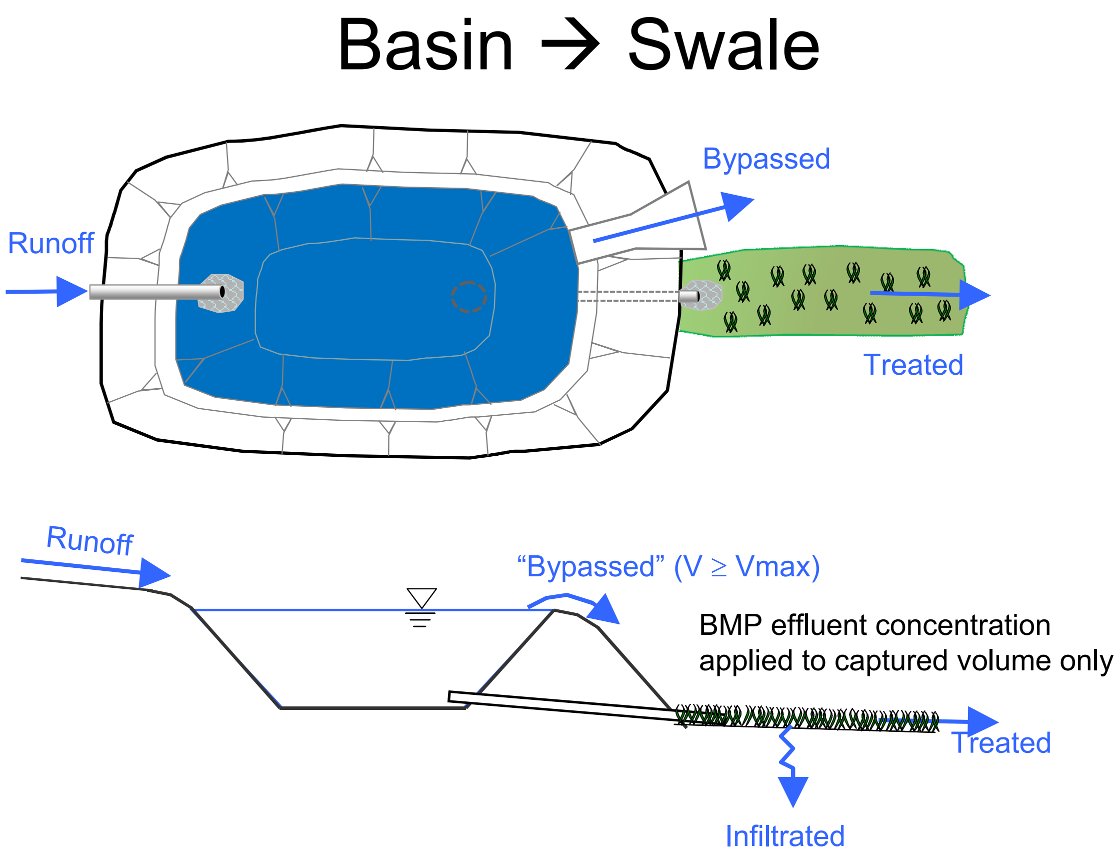


Figure 2C. Schematic plan and profile views of the Bioretention BMP selected for evaluation.

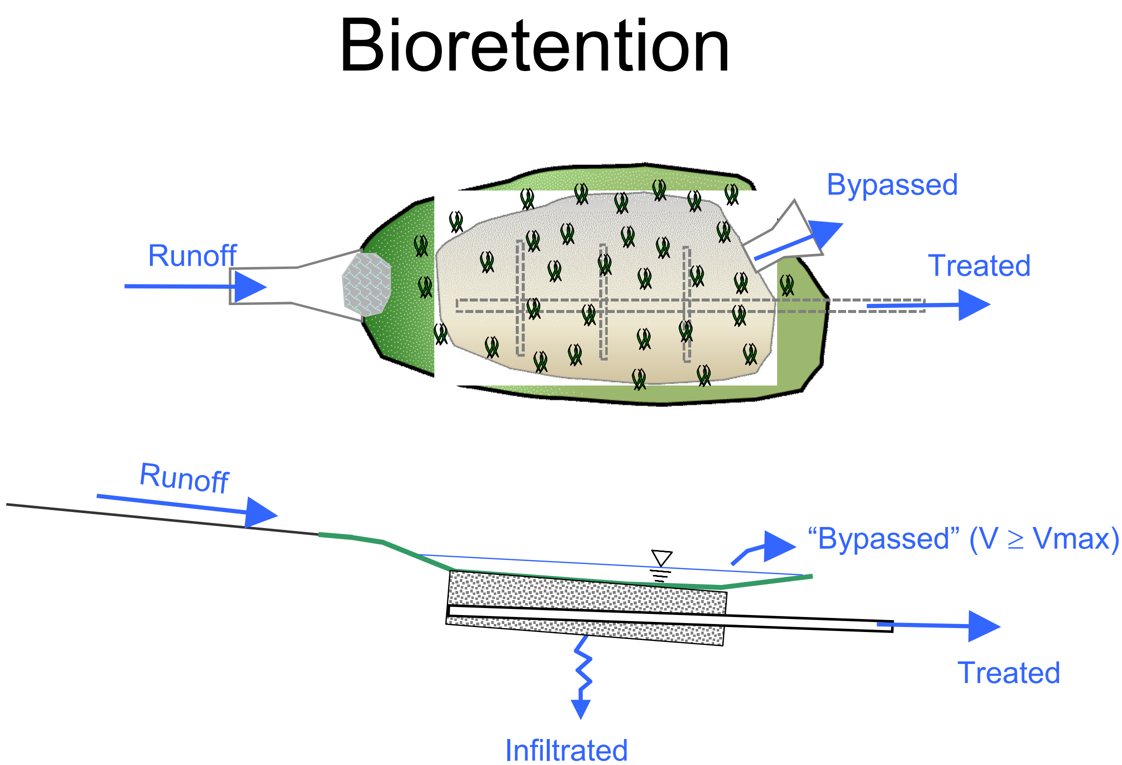


Figure 3. Rainfall distribution curves at Los Angeles International Airport (WY 1948-2004).

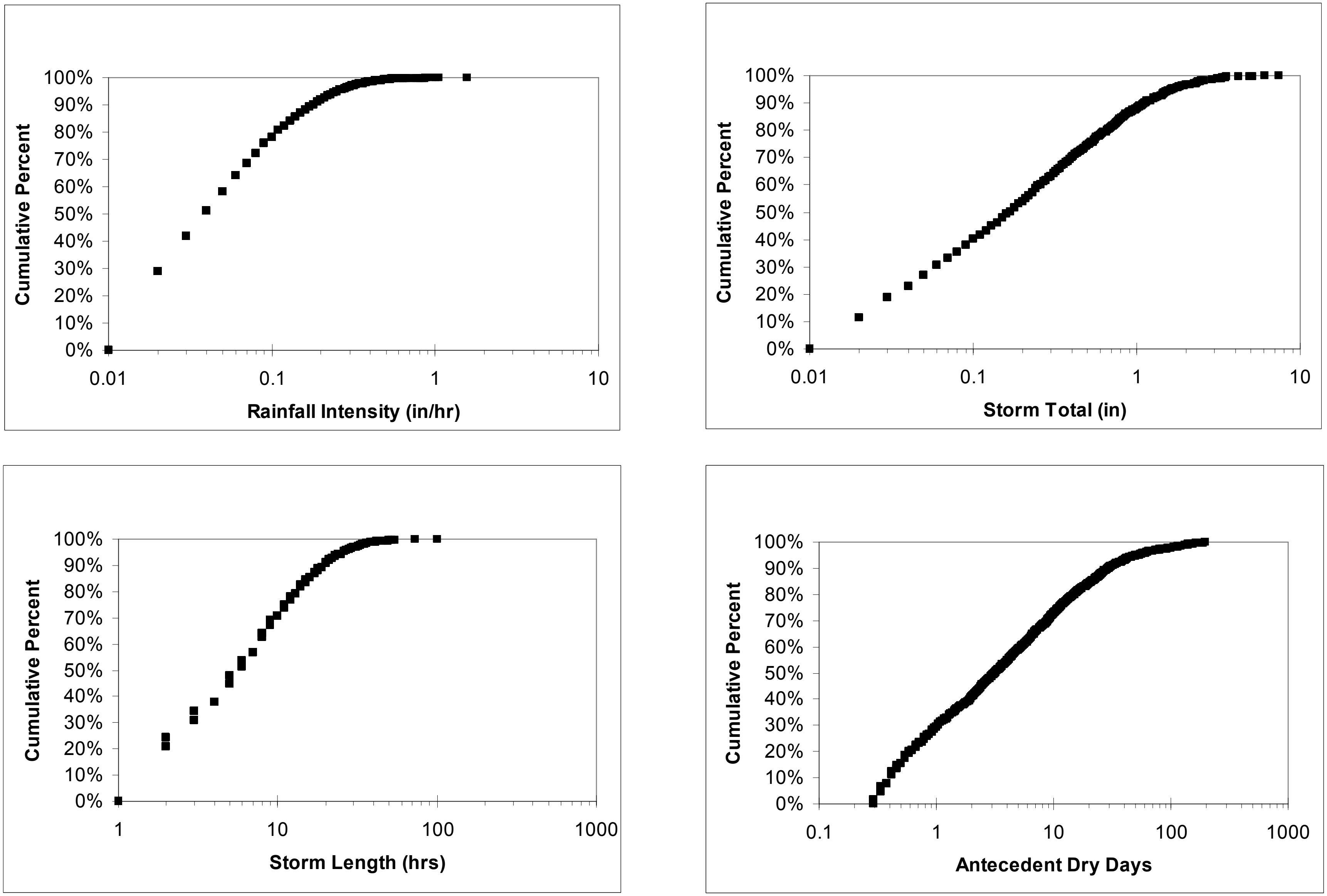


Figure 4. Mean daily flow duration curve for Ballona Creek.

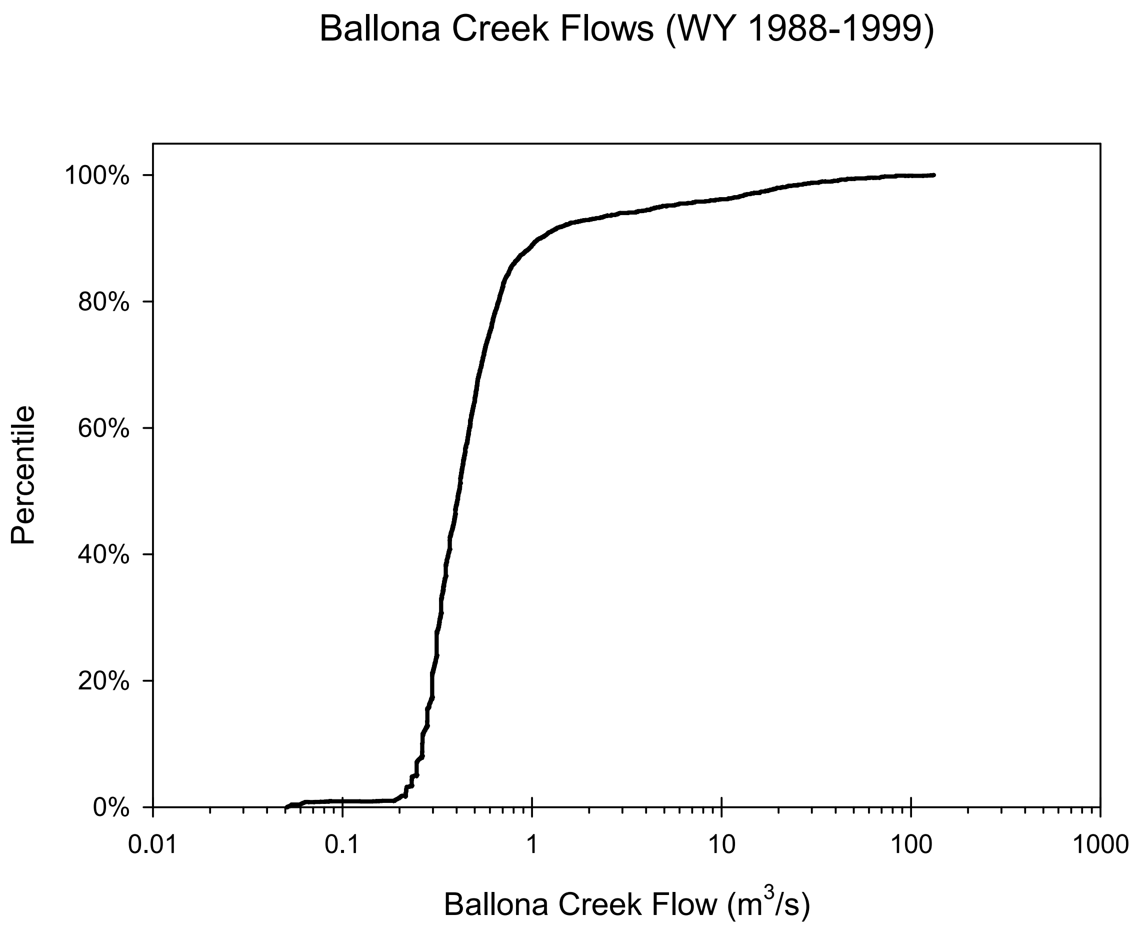


Figure 5. Percent of total runoff from Ballona Creek between 1971 and 2001 as a function of increasing precipitation volume.

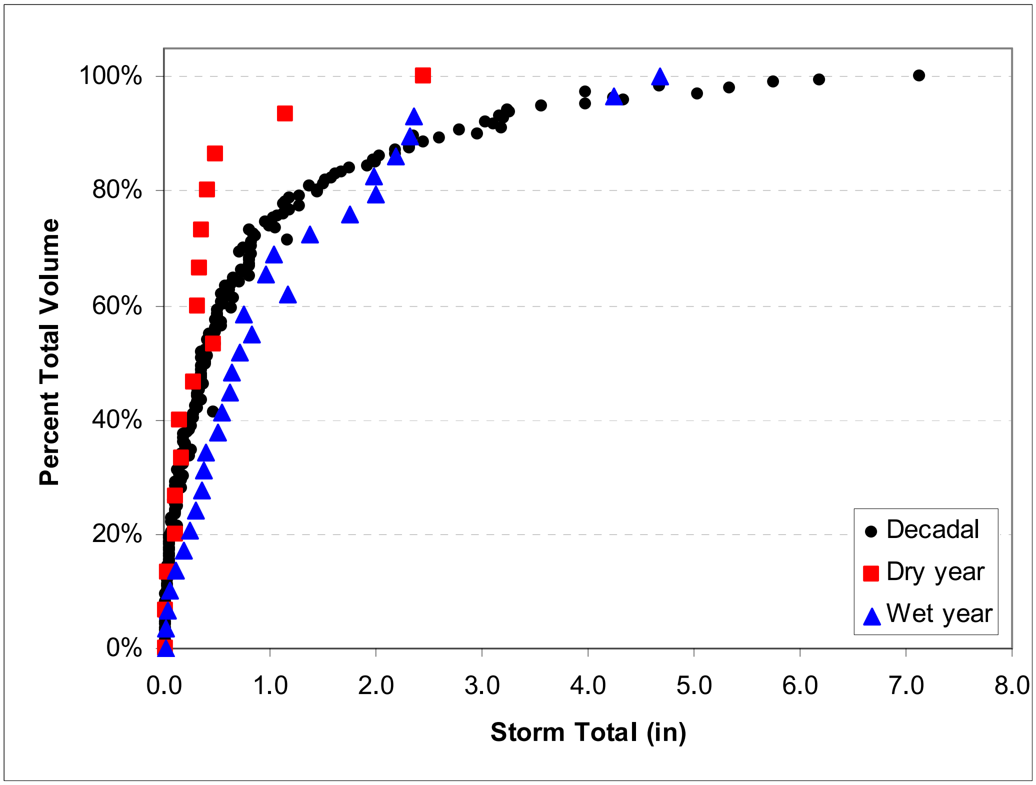


Figure 6. Percent of total copper load from Ballona Creek between 1971 and 2001 as a function of increasing storm precipitation volume.

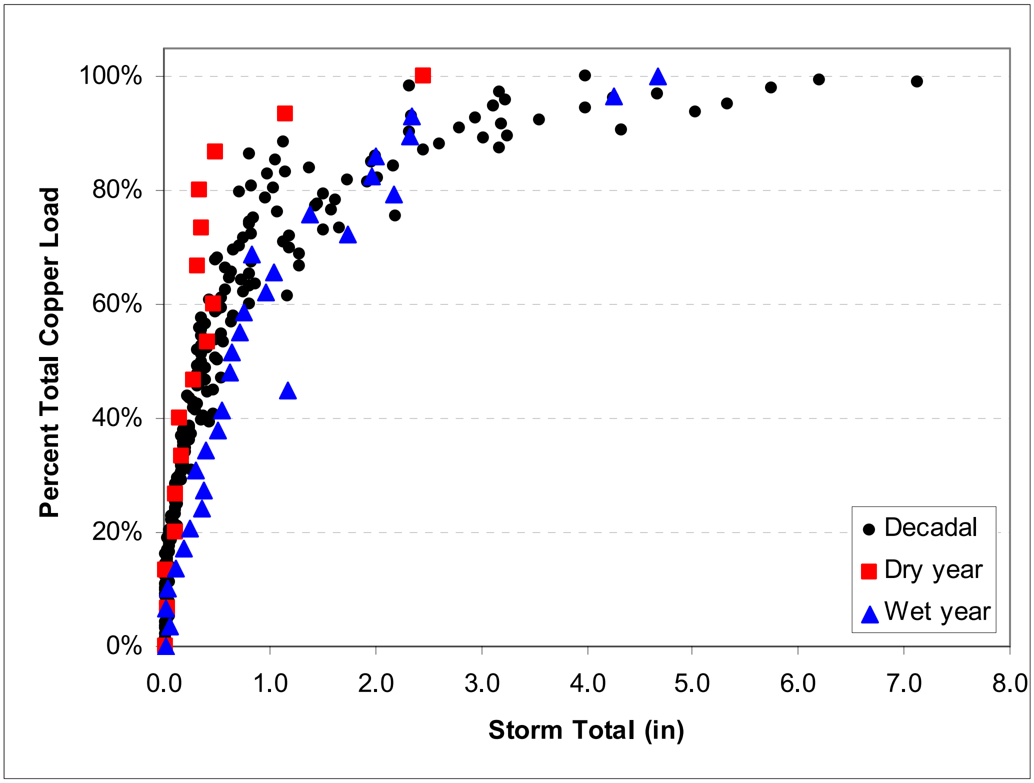


Figure 7. Relationship between rainfall volume and event mean concentration of total copper for Ballona Creek.

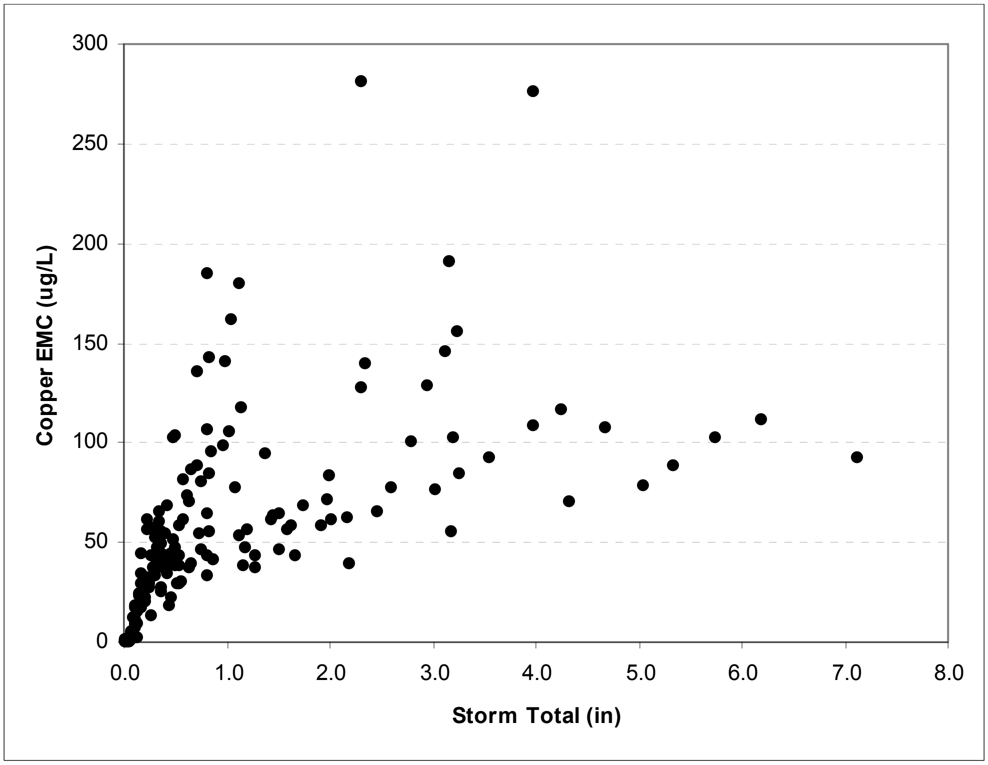
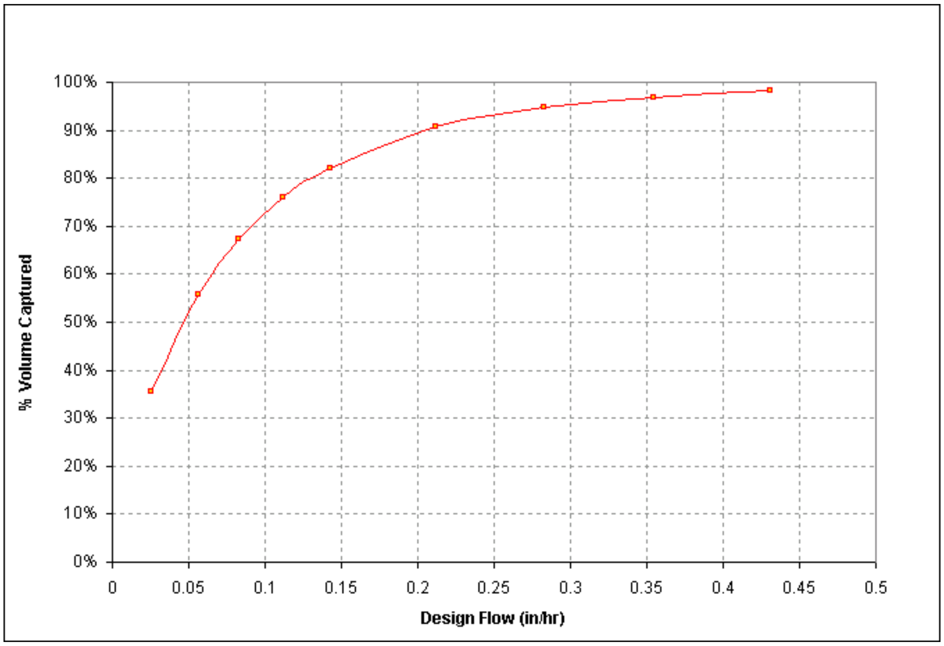


Figure 8. Performance characteristics for the swale BMP.



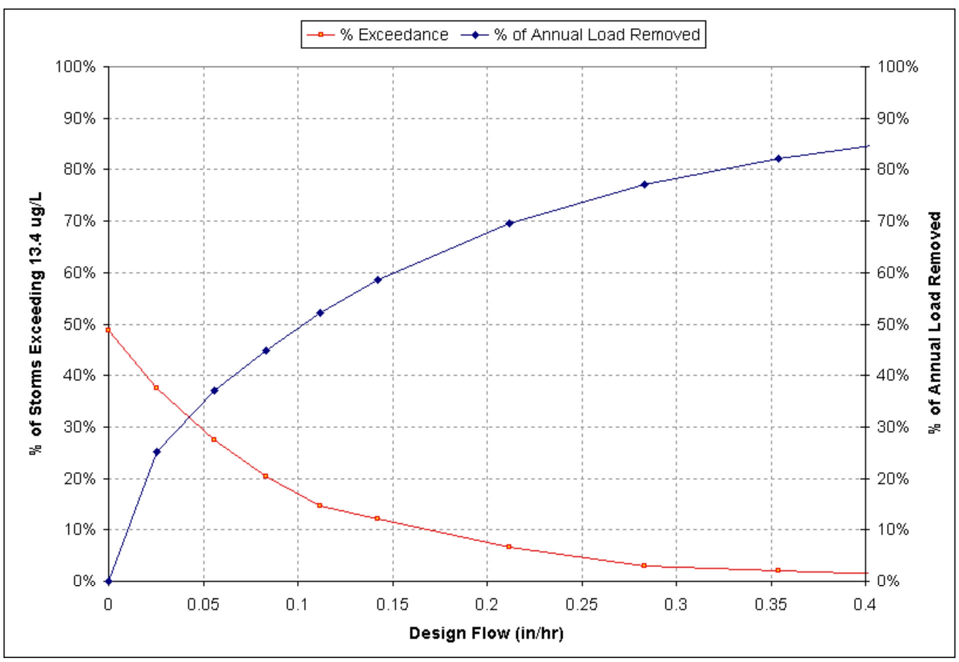
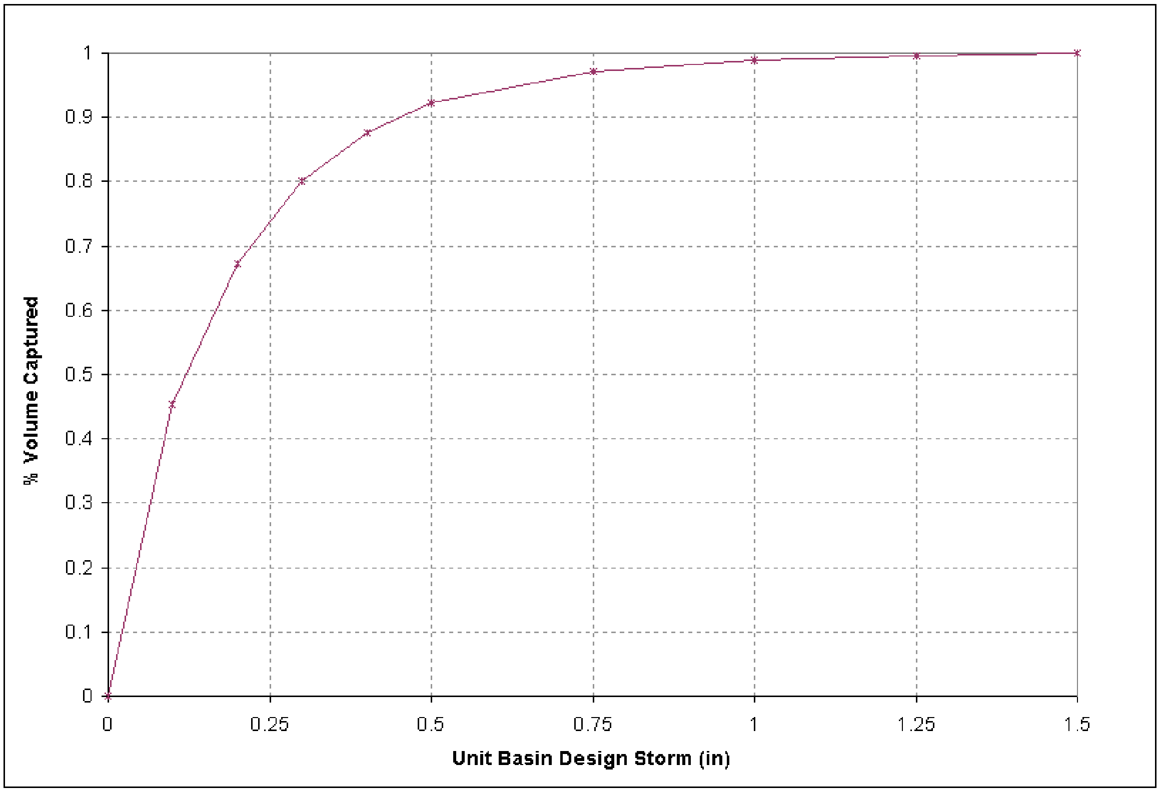


Figure 9. Performance characteristics for the flow-controlled swale BMP.



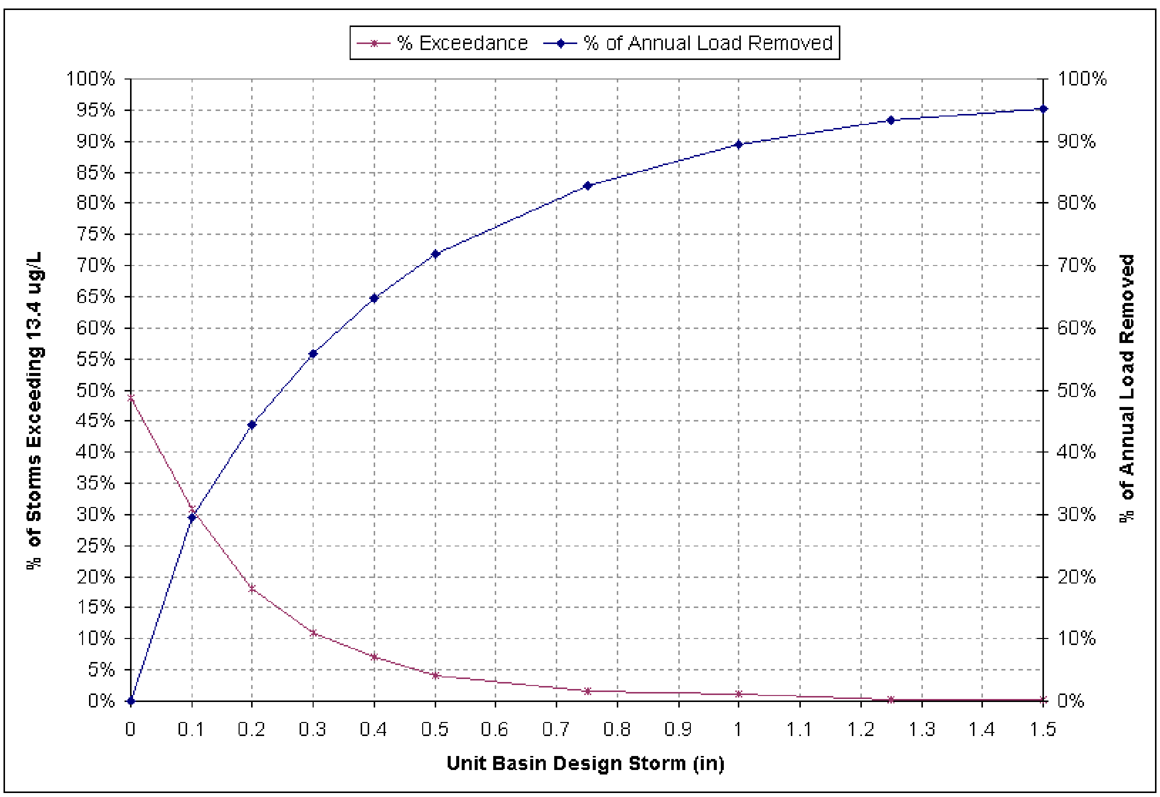
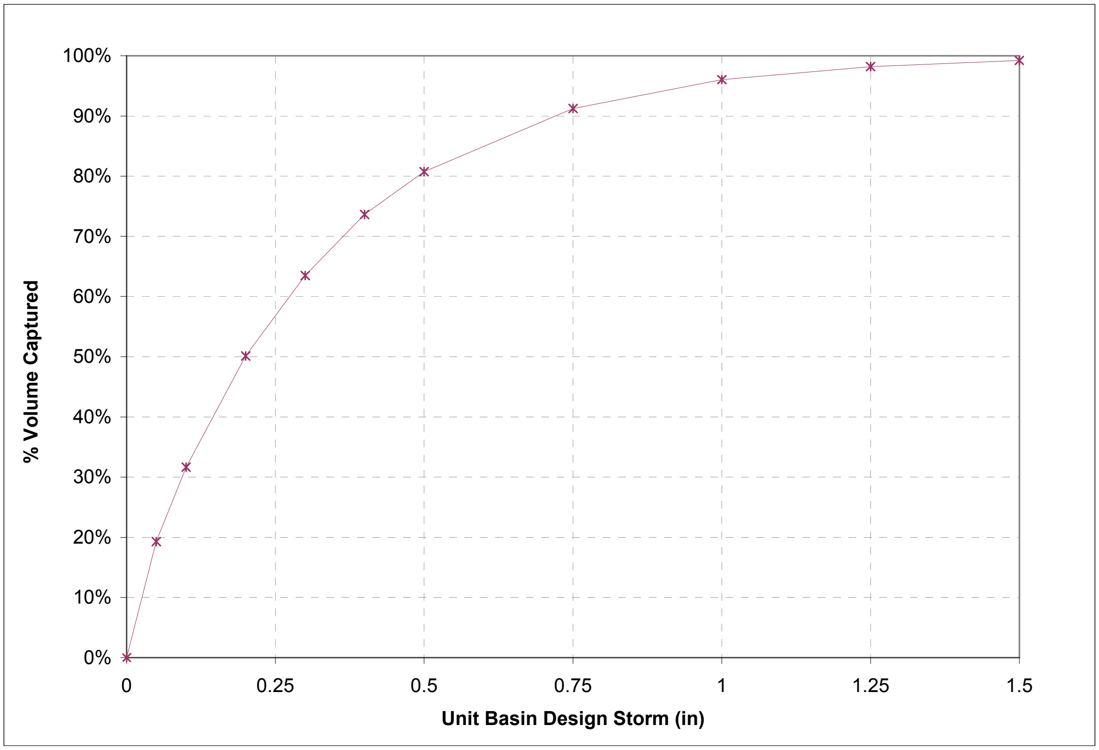


Figure 10. Performance characteristics for the bioretention BMP.



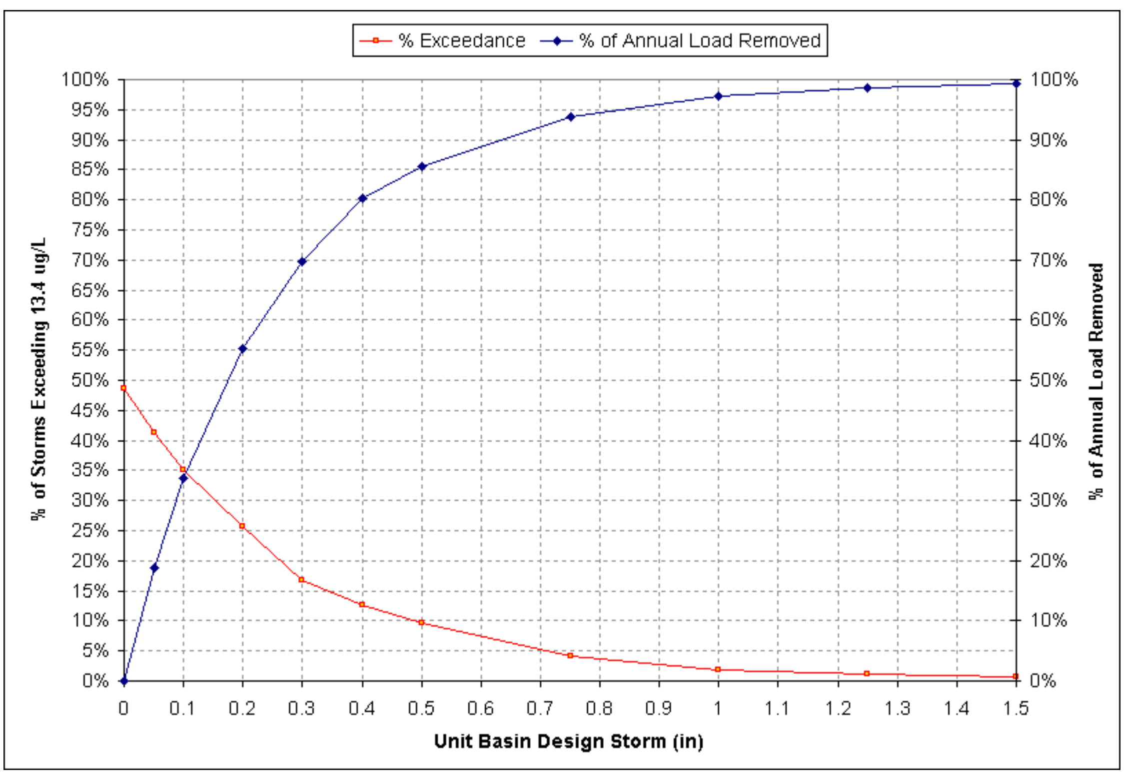


Figure 11. Difference in flow-controlled swale effectiveness with a 6-hr versus a 24-hr interevent time.

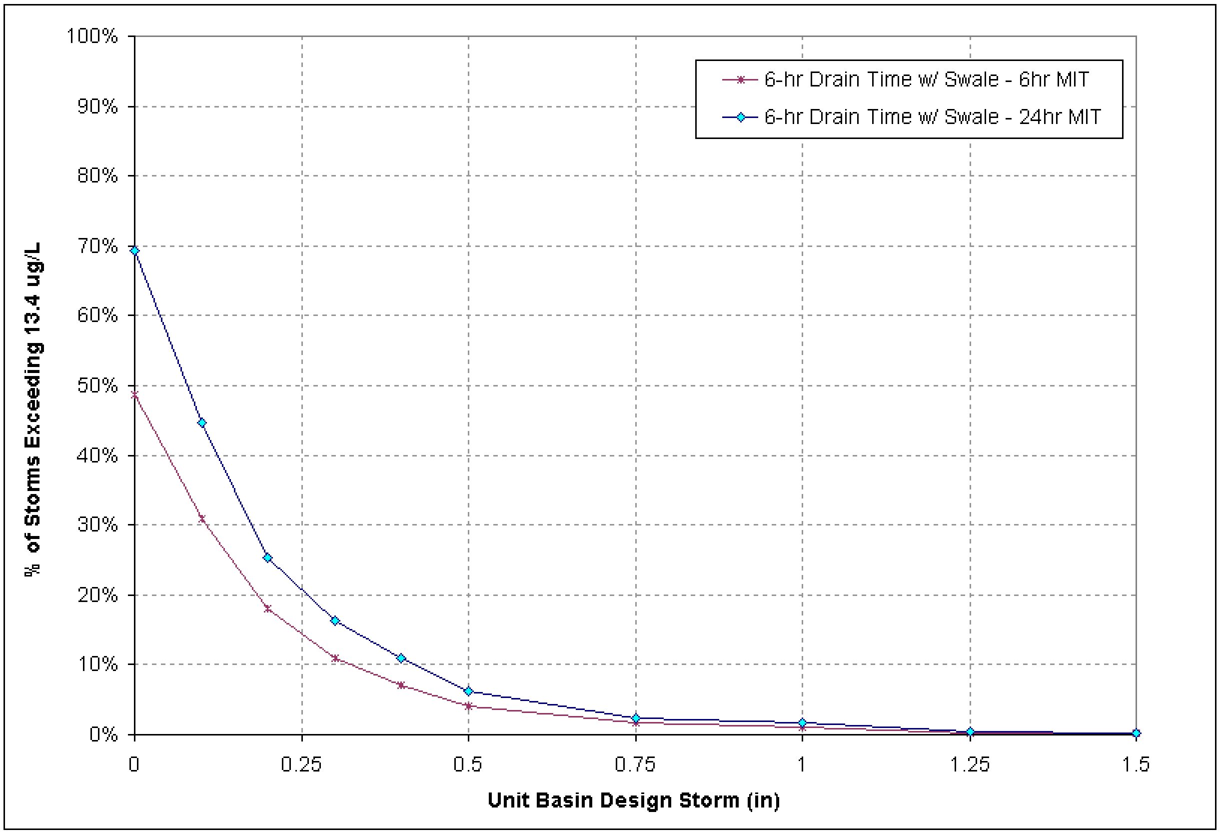


Figure 12. Difference in flow-controlled swale effectiveness with variations in water quality benchmarks.

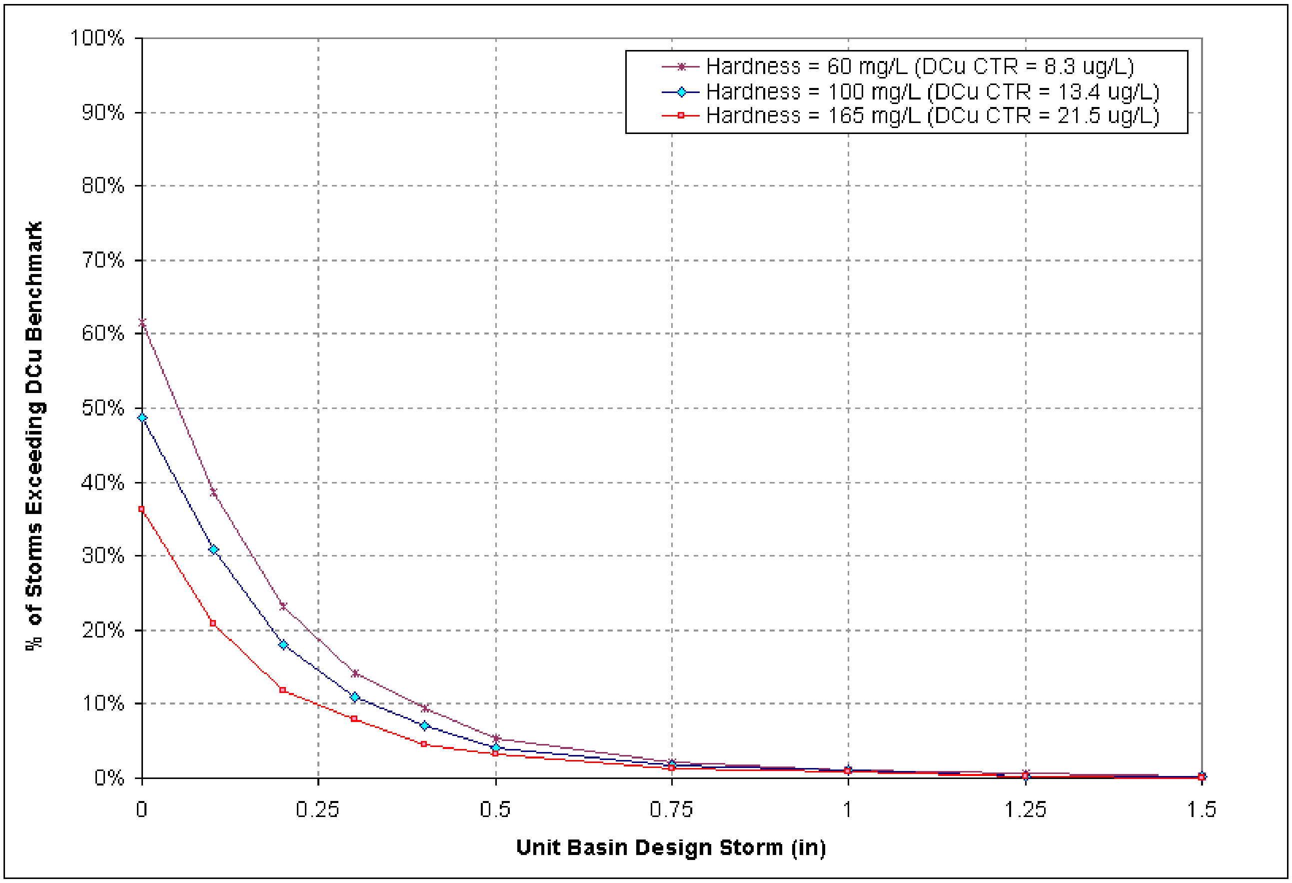


Figure 13. Comparison of load removal for the three targeted BMPs.

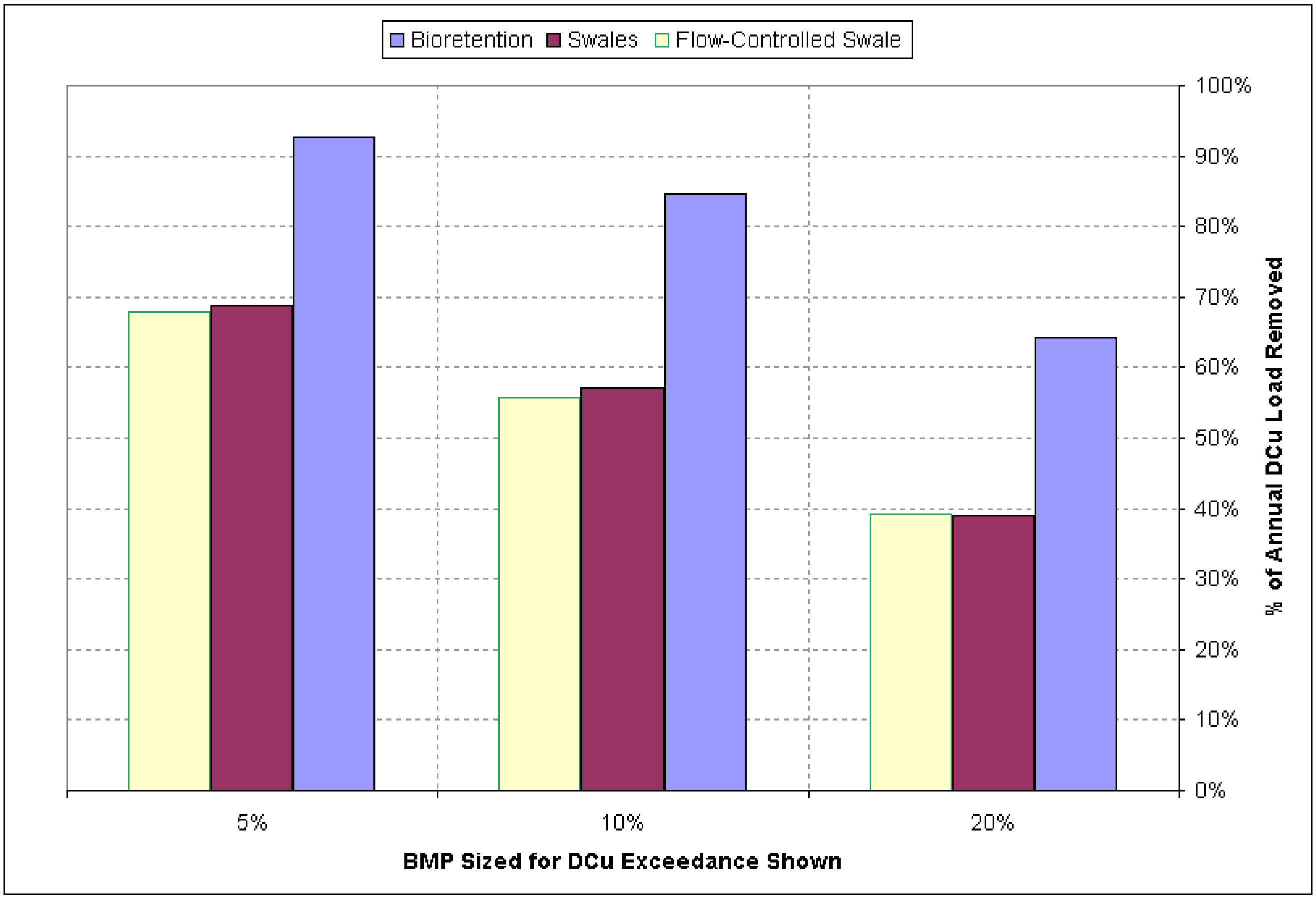


Figure 14. Footprint of the three targeted BMPs for various sizing standards.

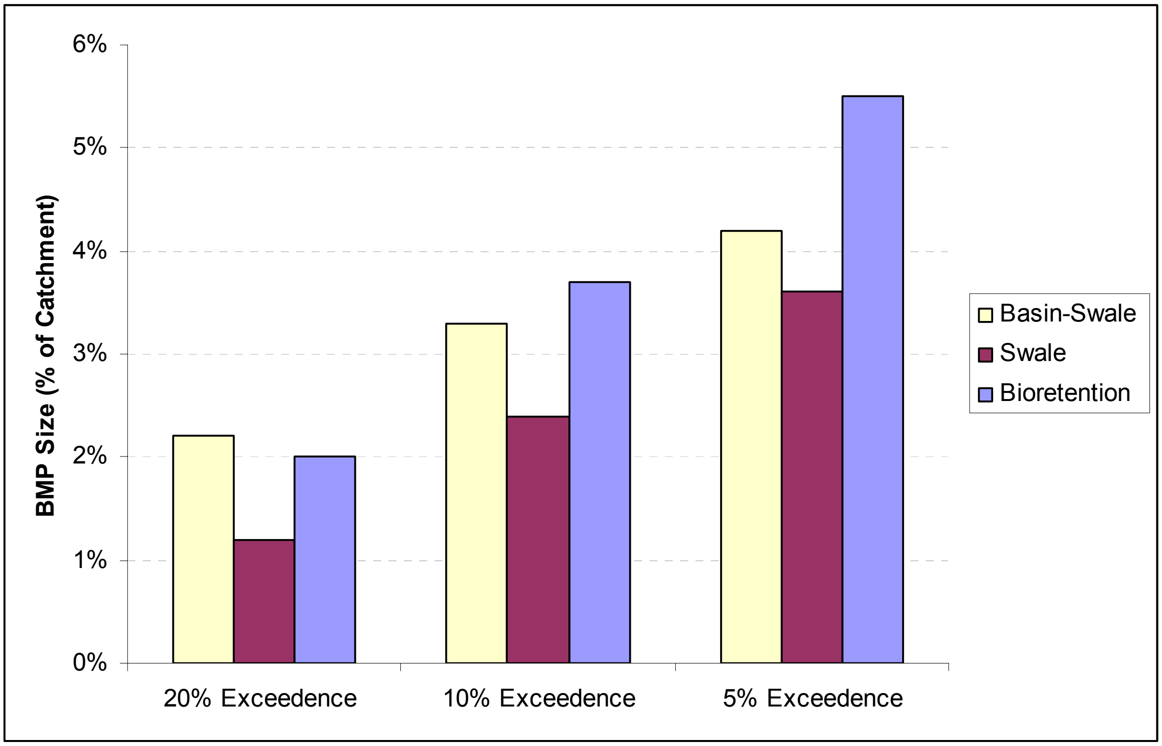


Figure 15. Load normalized cost estimates for the three BMP targeted in this study.

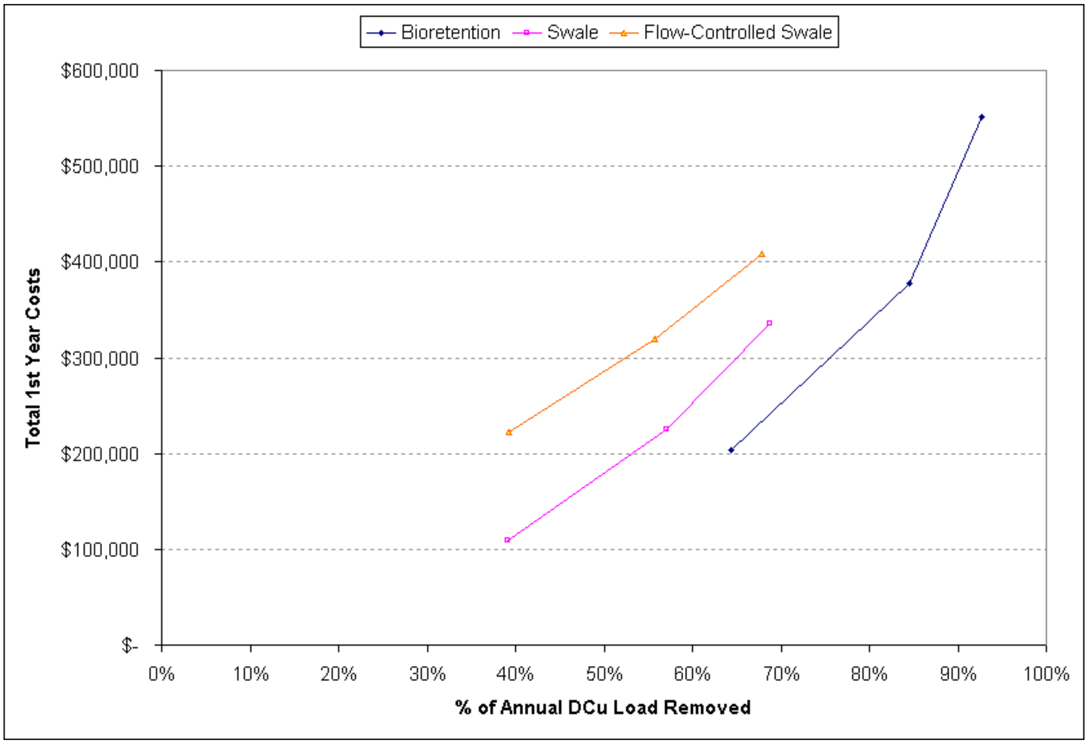


Table 1. Design criteria for three BMPs to meet modeled exceedence frequencies.

Exceedance Frequency	Swale	Flow-Controlled Swale	Bioretention
20%	0.08 in/hr	0.05 in/hr 0.18 in	0.26 in
10%	0.17 in/hr	0.09 in/hr 0.32 in	0.48 in
5%	0.25 in/hr	0.13 in/hr 0.45 in	0.7 in

Table 2. BMP footprint areas for three selected design sizes of each BMP type.

BMP Type	Design Size	Drainage Area Size (acres)	BMP Footprint (acres)	BMP Footprint (sq-feet)	Proportion of Drainage Area Dedicated to BMP (%)
Bioretention	20% Exceed	10.0	0.09	3,712	2.0%
Bioretention	10% Exceed	10.0	0.16	6,853	3.7%
Bioretention	5% Exceed	10.0	0.23	9,995	5.5%
Swale	20% Exceed	10.0	0.05	2,162	1.2%
Swale	10% Exceed	10.0	0.10	4,469	2.4%
Swale	5% Exceed	10.0	0.15	6,669	3.6%
Flow-Controlled Swale	20% Exceed	10.0	0.09	4,038	2.2%
Flow-Controlled Swale	10% Exceed	10.0	0.14	5,999	3.3%
Flow-Controlled Swale	5% Exceed	10.0	0.18	7,763	4.2%

Table 3. Cost estimates for the three targeted BMPs.

	Capital Costs		Annual Operations and Maintenance		Land Costs		Total 1st Year Costs	
BMP	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
Bioretention 20% Exceedance	$23,900	$39,800	$1,140	$2,280	$85,200	$255,600	$110,000	$298,000
Bioretention 10% Exceedance	$44,800	$74,700	$2,110	$4,210	$157,300	$472,000	$204,000	$551,000
Bioretention 5% Exceedance	$65,500	$109,200	$3,070	$6,140	$229,500	$688,400	$298,000	$804,000
Swale 20% Exceedance	$7,000	$11,700	$660	$1,330	$49,600	$148,900	$57,000	$162,000
Swale 10% Exceedance	$13,500	$22,400	$1,370	$2,750	$102,600	$307,800	$117,000	$333,000
Swale 5% Exceedance	$20,000	$33,400	$2,050	$4,100	$153,100	$459,300	$175,000	$497,000
Flow-Controlled Swale 20% Exceedance	$27,400	$45,700	$780	$1,510	$92,700	$278,100	$121,000	$325,000
Flow-Controlled Swale 10% Exceedance	$32,200	$53,700	$1,050	$2,060	$137,700	$413,100	$171,000	$469,000
Flow-Controlled Swale 5% Exceedance	$37,000	$61,600	$1,330	$2,610	$178,200	$534,700	$217,000	$599,000

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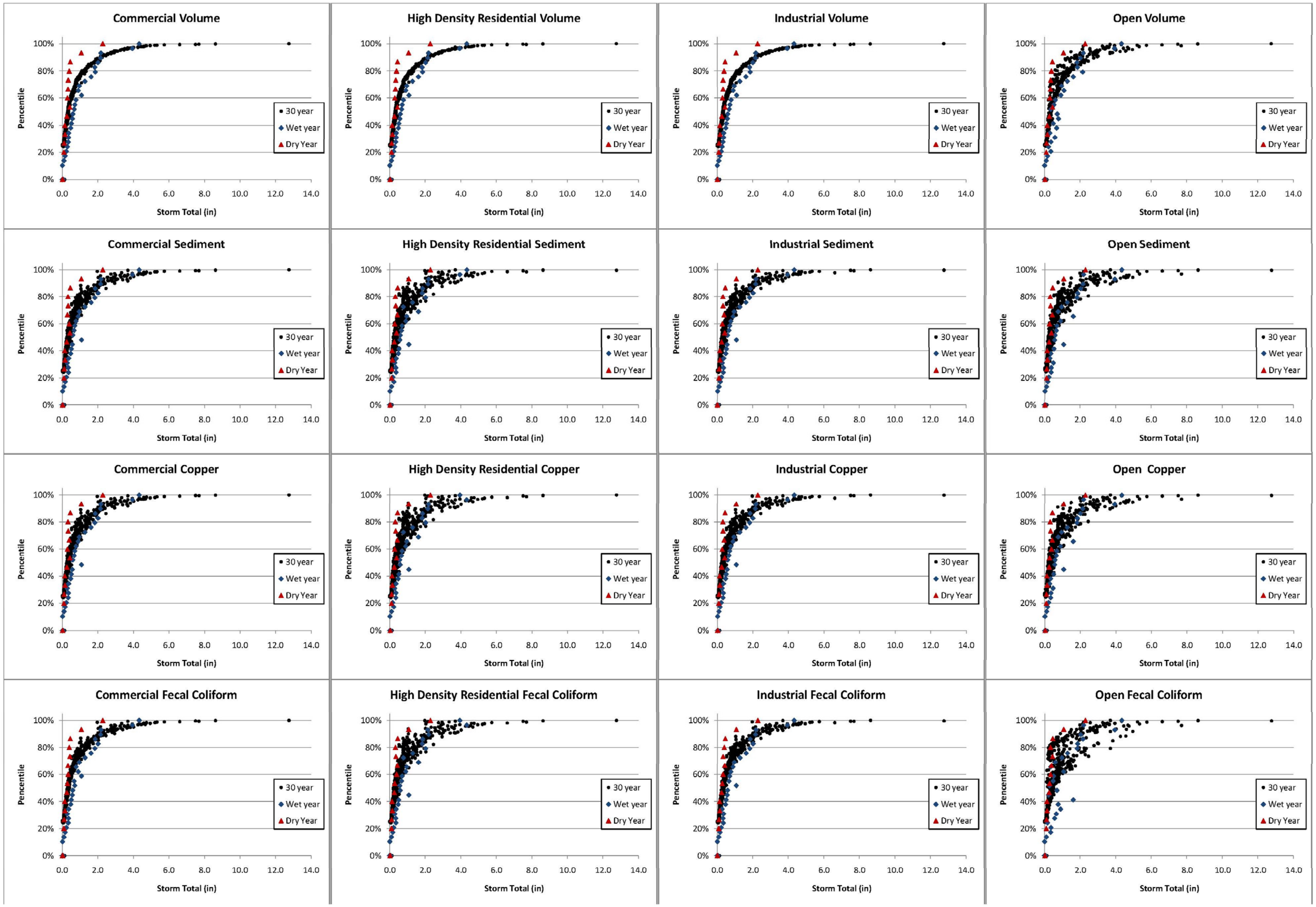
APPENDIX A

The focal point of this report was copper because of the trace metal TMDL for Ballona Creek. However, one recommendation was that design storm standards should be developed for additional water quality constituents and other land uses. The working group began to explore this issue using the runoff model HSPF, which had been calibrated for additional land uses and other constituents. While BMP scenarios were not developed for these other land uses or water quality constituents, 30-year simulations (1971 – 2001) estimating runoff loads were conducted (Figure A1). These simulations included runoff volume, total suspended solids, total copper, and fecal coliform bacteria. Like the simulations in the report that utilized a generic 10-acre high density residential catchment, the runoff model was also applied to a generic 10-acre commercial, industrial, or open (undeveloped) land uses. Mimicking Figure 5 and 6 in the report, the cumulative distribution of loads was modeled over the 30-year simulation as a function of precipitation volume. Maximum year-to-year variance was shown as the same plot, but using the only the wettest and driest water years during the modeling period.


Commercial Volume
High Density Residential Volume
Industrial Volume
Open Volume
Commercial Sediment
High Density Residential Sediment
Industrial Sediment
Open Sediment
Commercial Copper
High Density Residential Copper
Industrial Copper
Open Copper
Commercial Fecal Coliform
High Density Residential Fecal Coliform
Industrial Fecal Coliform
Open Fecal Coliform
Pencentile
Storm Total (in)
30 year
Wet year
Dry Year