Evaluating the effectiveness of Best Management Practices using dynamic modeling

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ABSTRACT

Structural Best Management Practices (BMPs) have become a tool for stormwater managers to achieve water quality improvement and regulatory compliance. Reliance on empirical evaluation limits the ability to predict BMP performance under varying situations. This study applies a dynamic model to simulate BMP performance. A BMP model used output from a calibrated and validated land-use model to evaluate two BMP types, a retention facility and flow-through swale. The model evaluated each BMP alone and in series targeting volume, total suspended solids, and total copper. Effectiveness was based on load reduction, event mean concentrations, and water quality exceedence frequency. The model predicted over 60% removal of solids and copper over most conditions; however, effectiveness was reduced during large storms and wet years. Although performance was similar based on load reduction and water quality standard exceedence, the latter was most sensitive to storm size. This study demonstrates that BMP modeling can help managers understand expected BMP performance over a range of storms, time periods, and design parameters, and, perhaps more significantly, evaluate BMPs in series.

INTRODUCTION

Stormwater runoff from developed areas is frequently associated with elevated pollutant levels (Boulanger and Nikolaidis 2003). Because these pollutant levels can result in adverse effects to receiving waters (Bay *et al.* 1998), they are often the subject of regulatory and management attention. One of the most common management approaches used over the last ten years has been the construction of structures or facilities aimed at capturing or treating runoff prior to it entering streams or receiving waters (i.e., structural BMPs; Sample *et al.* 2003).

Despite the widespread use of structural BMPs, there is still a fair amount of uncertainty over their effectiveness over a range of applications and circumstances (USEPA 2000a). This uncertainty is due to the fact that BMP effectiveness is typically assessed by empirical evaluation in particular settings, making it difficult to generalize the findings of any given assessment. The uncertainty is exacerbated by the fact that effectiveness can be measured in a variety of different ways (e.g., removal efficiency, effluent concentration), further complicating the ability to generalize the results of empirical observations (USEPA 2000b).

Dynamic models offer an alternative for evaluation of BMP effectiveness at improving water quality. Computer models have been extensively used to mimic the response of watersheds to various rainfall scenarios. Modeling has been used to simulate runoff and water quality from a variety of land use and watershed types (e.g., Im *et al.* 2003, Brun and Band 2000, Fontaine and Jacomino 1997). Additional work has investigated the effect of BMPs on reducing peak flows, volume, and water quality loadings to receiving waters (e.g., Clear Creek Solutions 2006, Coon 2003, Cryer *et al.* 2001, Moore *et al.* 1992). Most BMP modeling has relied upon standard "BMP performance" values obtained from the literature for prediction of their effect on water quality. To date, there has been limited application of dynamic simulations to mechanistically evaluate BMP water quality performance and effectiveness at improving instream water quality on a storm-by-storm basis.

In this study, we demonstrate the application of a dynamic simulation model, the Low-Impact Development Management Practices Evaluation Computer Module (BMP Module; Tetra Tech 2006), to evaluate the effect of several BMP types at reducing pollutant runoff (loads and concentrations) from a generic land use parcel. This approach builds on past work done in the greater Los Angeles, California, USA region where previous studies have characterized the changes in water quality runoff from single land use catchments and watersheds throughout a storm using a fully calibrated and validated model based on the Hydrologic Simulation Program-Fortran (HSPF; Ackerman and Weisberg 2006, Bicknell *et al.* 2001, Ackerman *et al.* 2005). This study builds on the previous work by coupling the BMP Module to the existing HSPF model to enable an evaluation of the BMP performance throughout a storm. This approach also enabled the pollutant concentrations discharging from the BMP to be compared to water quality criteria to determine the magnitude and extent that that runoff is in exceedence of water quality standards.

The goal of this study was to develop a model for direct simulation of BMP performance over a wide range of storms and different BMP types. The model was used to test the performance of two different BMPs independently and in series. A ten-year simulation was used to evaluate performance over a range of rainfall patterns. Assumptions regarding the BMP design were varied and their impact evaluated. This allowed for a demonstration of how direct BMP simulations can be used to characterize performance over a range of design and application scenarios.

METHODS

The BMP Module (Tetra Tech 2006) was selected to simulate BMP performances. It can be used in series with the output from HSPF to process stormwater runoff information from the HSPF simulation through two general BMP types. One type of BMP retains water discharges through an orifice and spillway; examples include bioretention basins, dry wells, and cisterns. The other BMP type has water flowing through an open channel with bank overflow; examples include grass swales, sand filters, and buffer zones.

The processes simulated for these the two general types of BMPs represent the majority of BMP types typically used. Processes simulated in retention BMPs include evapotranspiration, infiltration into a soil layer within the BMP and infiltration into the underlying soil. Outflow from retention BMPs includes overflow from a weir that controls the depth of the standing water in the BMP, flow from an orifice to drain the BMP and flow from an underdrain between the two soil layers. Processes simulated for the flow through BMP include infiltration, flow down the length of the channel, or overspill at the maximum design depth. For both BMP types we assumed that first order degradation processes operated on the pollutants within the BMP. In addition, the retention and BMP also had a percent removal applied to the flow from the underdrain.

Two example BMPs were selected for simulation in high density residential areas. Bioretention basins and a dry swale were selected for simulation on a 4,000-m^2 (1-acre) catchment. The catchment size was chosen to define a unit-process so that future incorporation into the HSPF watershed model could be easily extrapolated. A third type of BMP was simulated, a planter box, but it was assumed to operate with the same processes and rates as the bioretention basin. The BMPs were applied independently and the planter box and dry swale, respectively, were applied in series.

Watershed Model

The BMP simulation was based on previous work that calibrated and validated hydrologic and water quality models using HSPF. The hydrologic model was calibrated and validated to decadal simulations (WY 1990-1999) in the urbanized Ballona Creek and nearby, less developed Malibu Creek watersheds. The model evaluation used the first five years of the simulation for calibration with respect to identical model coefficients, and the second five years for validation. The daily average storm flows calibrated and validated reliably, with correlation coefficients greater than 0.8 (Ackerman *et al.* 2005).

Water quality models were then built upon the knowledge gained from the hydrology model. Twenty-one site events were modeled for calibration from six land uses (agriculture, commercial, high density residential, industrial, low density residential, and open) over a four-year period. Rainfall quantity ranged from 2.03 mm to 32.5 mm per event, and antecedent dry days varied from 3 to 31 days. The single land use catchments ranged from 0.02 to 9.49 km^2. Average calibration error was 40% and 30% of the measured load for copper and suspended solids, respectively. The calibrated parameters were applied to Ballona Creek where seven storms were sampled. The validation model error was 39% and 33% of the measured load for copper and suspended solids, respectively catchments (Ackerman and Weisberg 2006).

The calibrated and validated model was then applied to a theoretical 4,000-m^2 catchment representing a single land use type (high-density residential). Decadal HSPF simulations (WY 1990-99) for hydrology and water quality (suspended solids, and total copper) were made for a high density residential and open space catchment using the Los Angeles International Airport meteorological information (NCDC 2004). Figure 1 shows the storm rainfall for that simulation period (a storm was defined as a period with a preceding time of six hours or more without rain). The BMP module used the same meteorological data in its simulations. A total of 309 storms occurred during the simulation period and ranged from 0.03 to 7.82 cm with half of the storms being less than 0.5 cm.

Data

Two broad categories of data are required to develop and apply the BMP model. First, data is needed to characterize the performance of the BMPs. Second, information is required to accurately characterize the local conditions (i.e., infiltration rates, evapotranspiration potential).

Data on BMP performance primarily came from two sources. The International Stormwater Best Management Practices database (www.bmpdatabase.org) is the best source for raw BMP performance data. The database typically includes inflow and outflow volumes and water quality concentrations. Physical descriptions of the BMPs are often included as well. Table 1 and Figure 2 summarize the average load removal efficiency of the two types of BMPs evaluated from the BMP database.

Performance was based on a percent reduction compared to the high density residential simulations via:

$$\text{Percent Reduction} = \frac{\text{Effluent Load}}{\text{Influent Load}} - 1$$

Events with effluent volume greater than influent were excluded from the analysis (Figure 2).

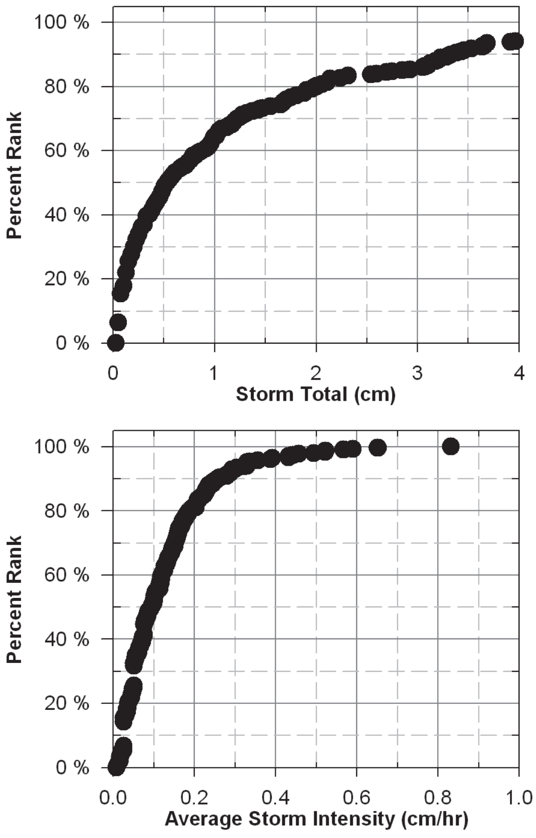

Figure 1. Storm characteristics during the WY 1990-1999 simulation periods at the Los Angeles International Airport.

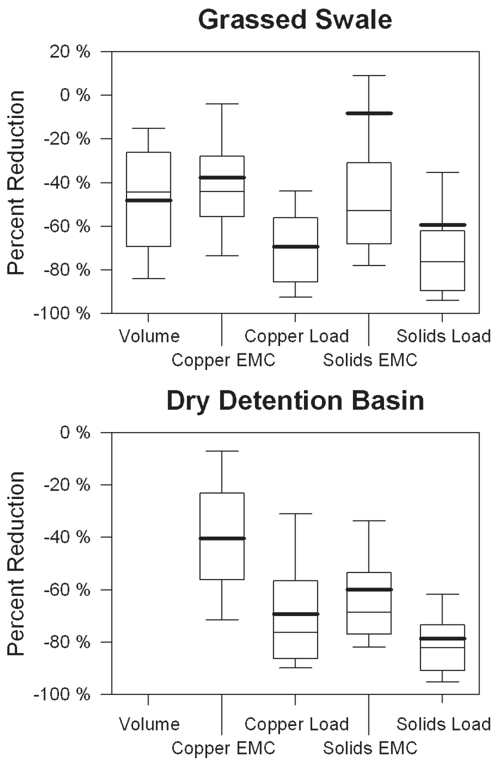

Figure 2. BMP removal efficiencies reported in the International BMP database. In the box plots, the whiskers represent the 90th and 10th percentiles and the upper and lower bounds of the boxes are the 75th and 25th percentiles. The horizontal dark line is the median value and the lighter horizontal line is the mean.

Table 1. Percent removal of pollutant loads from BMPs in the International Stormwater BMP database.

	State		Reductions		
		Count	Volume	Solids	Copper
Bioretention Basin					
Greenville Pond	North Carolina	8	-14%	-75%	-43%
I-15/SR-78 EDB	California	5	-28%	-79%	-77%
I-5 / SR-56	California	7	-32%	-78%	-71%
I-5/Manchester (east)	California	12	-38%	-79%	-74%
I-605 / SR-91 EDB	California	11	-77%	-88%	-85%
Lexington Hills - Detention Pond	Oregon	11	-56%	-71%	-63%
Grassed Swale					
Cerritos MS	California	6	-65%	-75%	-82%
Dayton Swale	Washington	3	-65%	-82%	-81%
I-5 North of Palomar Airport Road	California	8	-28%	-69%	-64%
I-5/I-605 Swale	California	7	-50%	-80%	-67%
I-605 / Del Amo	California	3	-49%	-84%	-78%
I-605/SR-91 Swale	California	4	-66%	-64%	-67%
Russell Pond Bioswale	Oregon	6	-77%	-68%	-76%
SR-78 / Melrose Dr	California	5	-67%	-41%	-90%
WPCL Bioswale East	Oregon	9	-37%	-76%	-59%
WPCL Bioswale West	Oregon	9	-21%	-67%	-55%

Data on BMP performance from both lab-controlled simulations as well as installed BMPs has also been reported in the peer-reviewed literature. Usually, the raw data for the monitored events are not presented but rather the percent reduction for each monitored event is reported. Table 2 summarizes the results from various peer-reviewed sources. Davis *et al.* 1998 constructed BMPs in the lab and measured the flow and concentrations from the surface and sub surface layers in two bioretention basins.

Table 2. BMP load reductions as reported in peer-reviewed literature.

		Bioretention Basin		Grassed Swale		
Reference	**State**	**Solids**	**Copper**	**Solids**	**Copper**	**Comments**
Dorman 1989	Florida			98%	65%	185 ft, pct load removed
Harper 1993	Florida			87%	89%	210 ft, pct load removed
Harper 1993	Florida			81%	56%	210 ft, pct load removed
Kercher 1983	Florida			99%		Pct concentration removed
Wang 1981	Washington			80%	70%	
Davis *et al.* 1998	Maryland		96 - 98%			Lab experiments
PGDER 1993	Washington	90%				
USEPA 2000a	Maryland		43 ± 11%			Field test
Davis *et al.* 2001	Maryland		94%			Small prototype, upper layer
Davis *et al.* 2001	Maryland		94%			Small prototype, lower layer
Davis *et al.* 2001	Maryland		90%			Large prototype, upper layer
Davis *et al.* 2001	Maryland		93%			Large prototype, lower layer
Davis *et al.* 2003	Maryland		97%			Field test

Others (e.g., Dorman *et al.* 1989, Harper and Herr 1993) monitored influent and effluent to determine BMP efficiency.

Local infiltration rates were defined with local data. Data from infiltration spreading grounds operated by the Los Angeles Department of Public Works were used as input parameters (Ben Willardson, personal communication). Infiltration rates from various spreading grounds are presented in Table 3.

Model Hydrology

The model simulated runoff from a high density residential catchment. The BMPs that were selected reflected those that have a reasonable potential to be applied to high density residential parcels. A bioretention basin was selected and all the runoff from the site was routed through it. A dry swale was considered as a likely BMP as it could be placed adjacent to a sidewalk and thus treat all runoff from the land use catchment. Finally, we evaluated putting a small bioretention basin (an infiltration planter box) in series with a dry swale to capture runoff from the impervious areas.

The model for the bioretention basin simulated the capture of runoff from both the pervious and impervious areas. The utility Win-TR55 version 1.00.08 (NRCS 2005) was used to develop a runoff curve number for the site. We assumed that the 4,000-m^2 (1-acre) catchment had 40% cover of good grass cover and 60% cover of residential with class B soils, which resulted in a curve number of 0.69. That information was used in conjunction with a Bioretention Worksheet (Prince George's County 2005) to simulate a bioretention basin size of 246 m^2 (2,650 ft^2) for our 4,000-m^2 catchment. The bioretention basin was designed to retain 0.15 m (0.5 ft) of water and infiltrate it at 0.75 cm/hr (0.3 in/hr) into 0.76 m (2.5 feet) of soils with a soil porosity of 0.3. An underdrain infiltrates 0.25 cm/hr (0.1 in/hr) into 0.61 m (2 feet) of soils with a soil porosity of 0.3 (Clayton and Scheuler 1996).

Table 3. Infiltration rates at Los Angeles Department of Public Works spreading grounds.

Facility Name	Percolation Rate (in/hour)	Percolation Rate (cm/hour)
Santa Fe Spreading Grounds	5.99	2.36
San Gabriel Coastal Spreading Grounds	1.97	0.78
Rio Hondo Coastal Spreading Grounds	1.46	0.58
Branford Spreading Grounds	0.32	0.13

The dry swales were simulated as a flow through BMP with no flow control structures or surface storage. The swales were modeled following guidance in Clayton and Scheuler (1996). The side slopes were 3:1, the longitudinal slope was 0.5%, the length was 122 m (400 feet), and the bottom width was 1.8 m (6 feet). The maximum depth, given the modeled runoff, was 0.08 m (0.25 foot) with a Manning's n of 0.15.

The final BMP analysis included an infiltration planter box and dry swale in series. The typical high density residential density is approximately 5 houses per 4,000-m^2 (1 acre). Placing both a bioretention basin and dry swale on a site seemed restrictive because of the footprint needed for each. To incorporate some bioretention on the sites, infiltration planter boxes treated runoff from the impervious areas. Design of the planter boxes followed guidance from the Rhode Island Department of Environmental Management (Millar *et al.* 2005). The planter boxes on the catchment were aggregated into one large BMP for the five houses. It was modeled as being 1.22 m (4 ft) wide and 38.1 m (125 ft) long and capable of storing 0.3 m (1 ft) of water before overflowing. The underlying soils were 0.76 m (2.5 ft) deep with a soil porosity of 0.3 infiltrating at 2.54 cm/hr (1.0 in/hour). The underdrain was 0.6 m (2 ft) deep with the same porosity and an infiltration rate of 0.5 cm/hr (0.2 in/hr). Overflow was routed directly to the dry swale.

Model Water Quality

Since BMP performance is often expressed as a percent reduction, the model was calibrated to the observed load reductions (Table 1). The 309 modeled storms were grouped into 12 bins by their total rain 0.12, 0.25, 0.51, 0.76, 1.02, 1.27, 1.91, 2.54, 3.18, 3.81, 4.45, and ≥5.08 cm (0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.75, 1.00, 1.25, 1.5, 1.75, ≥2 inch). The overall reduction in storm load by storm size was calculated. The first order degradation rates were calibrated for each BMP (bioretention basin and grassed swale) to have the reduction at a 2.5 cm (1 inch) storm to approximate observed reductions. No calibration was performed for the planter box: it was assumed that the planter box would function like the bioretention basin but at a smaller scale.

BMP Performance

Model performance was evaluated for storm loads, event mean concentrations (EMCs), and number of exceedences for each scenario (bioretention basin, grass swale, planter box, and planter box then grass swale). Volumetric reduction and the peak flow for each storm was extracted and compared with the pre-BMP simulation. Solids and copper load reductions were calculated by water year, month, and storm size. Event mean concentrations for each simulation were calculated and compared to the California Toxics Rule (CTR; USEPA 2000c) water quality standards. We assumed a hardness of 100 mg/L with acute toxicity that resulted in a standard of 13.4 ug/L (the comparison was conservative since the standard is based on dissolved copper and we simulated total copper). The model time series was compared to the CTR standard as well as the number of hours that the simulations exceeded the standard.

Sensitivity Analyses

Sensitivity analyses were used to evaluate the relative impact of key assumptions in a model. Sensitivity analyses were performed on both the bioretention basin and the grassed swale by modifying key parameters by ±25%. In the bioretention basin, its size, infiltration rate, soil depth, underdrain depth, background infiltration rate and degradation rates (first order decay within the BMP and percent removal from the underdrain) were modified. The grassed swale had its slope, width, length, infiltration rate, and degradation rates (first order decay within the BMP and percent removal from the underdrain) changed. The relative impact of each was evaluated in terms of effect on total load (reduction) and exceedence hours.

RESULTS

Volumetric Reductions

All BMPs resulted in a reduction of the total volume discharged from the 4,000-m^2 developed catchment. The reductions seen in flow and total copper concentrations in a large storm (11.48 cm) on January 6, 1993 are shown in Figures 3 and 4. The planter box, which was the smallest of the BMPs, had the smallest reduction (~10%) and the bioretention basin had the largest overall reduction (~60%). The percent reductions generally decreased with increasing storm size (Figure 5). The years with rainfall over 56 cm (22 inches, 1993, 1995, and 1998; Table 4) had the lowest volumetric reductions, while the remaining years had comparable volumetric reductions. Volume reductions did not vary by month for any of the BMP simulations (Figure 6).

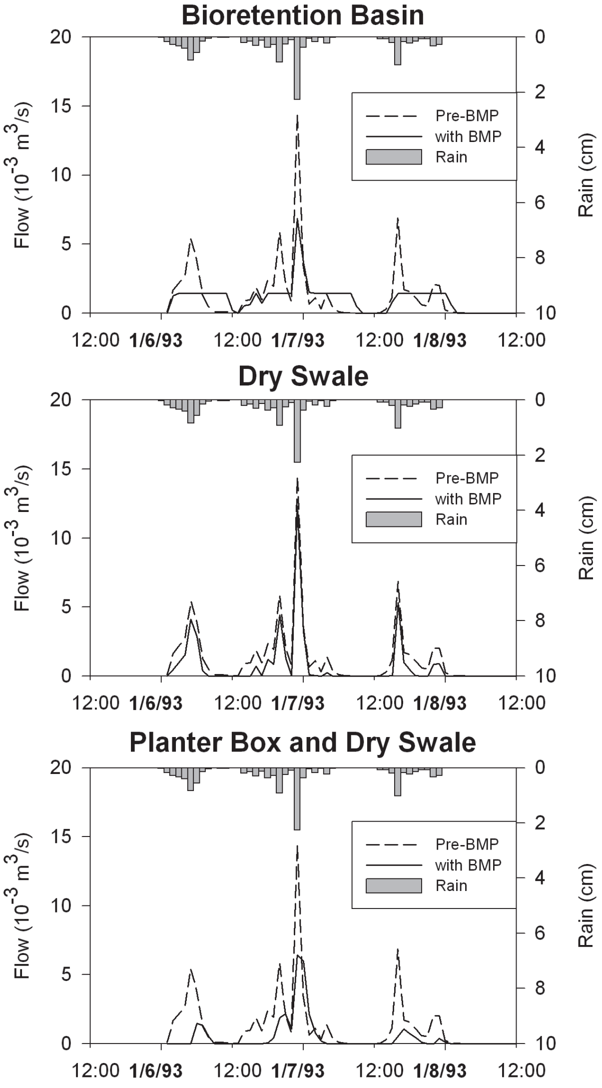

Figure 3. Modeled flow from the catchment before and after model BMP implementation. The total rain for the storm was 11.48 cm.

Peak Flow Reductions

All BMPs had the effect of reducing peak storm flows (Figure 7). The bioretention basin reduced peak flows more than the other individual BMPs. The grassed swale had a linear decrease in flow, removing 0.001 cms (0.04 cfs) from the system. Even though the planter box and grassed swale both had a relatively small decrease in the peak flow, their use in combination produced the largest overall decrease in peak flows.

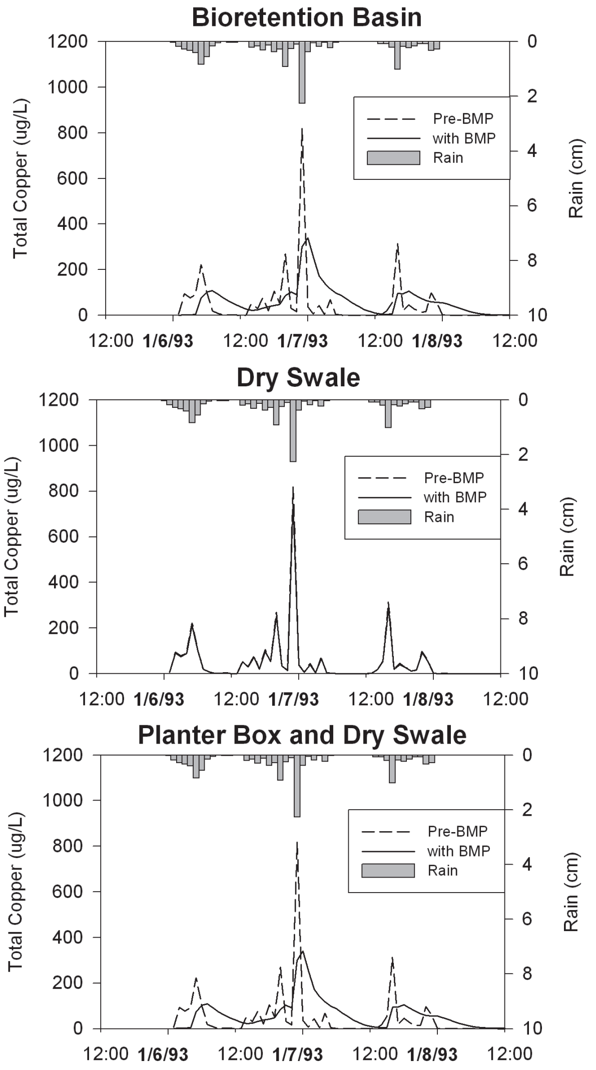

Figure 4. Modeled total copper concentrations from the catchment before and after model BMP implementation. The total rain for the storm was 11.48 cm.

Load Reductions

Sediment

The bioretention basin and planter box were able to remove over sixty percent of the solids load for all but the largest storms (Figure 6). The grassed swale retained over half of the sediment load in storms less than 0.76 cm (0.3 inch), with decreasing performance on larger storms.

The BMPs were most efficient at sediment retention in years with less than 51 cm (20 inches) of rain (Figure 6). In the El Niño years (1993 and 1998), the sediment loads were reduced by less than 50%, with the swales actually increasing loads. The performance in January and February, which had the greatest amount of rain (Table 5), was typically less than 50% reduction for all BMPs simulated.

Total copper

The copper reductions reflected those of the solids. The bioretention basin removed more than 90% of the total copper for all but the largest storms and the planter box removed more than two-thirds for those same storms. The grassed swale removed more than three-fourths of the load during storms less than 0.51 cm (0.2 inch), but was less efficient with increasing storm sizes (Figure 5). The lowest reductions of all BMP loads occurred during the wet El Niño years. Similarly, less total copper was captured by the BMPs during months with more rainfall and visa versa.

Water Quality Exceedence Reductions

The BMPs also reduced the frequency that the runoff EMC from the catchment exceeded CTR standards. Without BMPs, copper EMCs in runoff from the 4,000-m^2 parcel exceeded standards in 58% of the storms (Figure 8). The bioretention basin performed best at reducing EMCs to only 4% exceeding standards. The planter box and swale had EMCs exceeding 21 and 50% of the time, respectively. However, when those BMPs were utilized in series, their EMC exceedences dropped to 16%.

While an EMC can evaluate the general condition of runoff, equally significant is the time that the runoff is over water quality standards. Runoff from the high density residential catchment (without any BMPs)

Table 4. Water year rainfall totals at the Los Angeles International Airport.

Water Year	Rainfall (cm)	Rainfall (in)
1990	14.81	5.83
1991	20.98	8.26
1992	37.72	14.85
1993	59.28	23.34
1994	20.85	8.21
1995	58.06	22.86
1996	25.98	10.23
1997	33.78	13.3
1998	78.21	30.79
1999	23.09	9.09

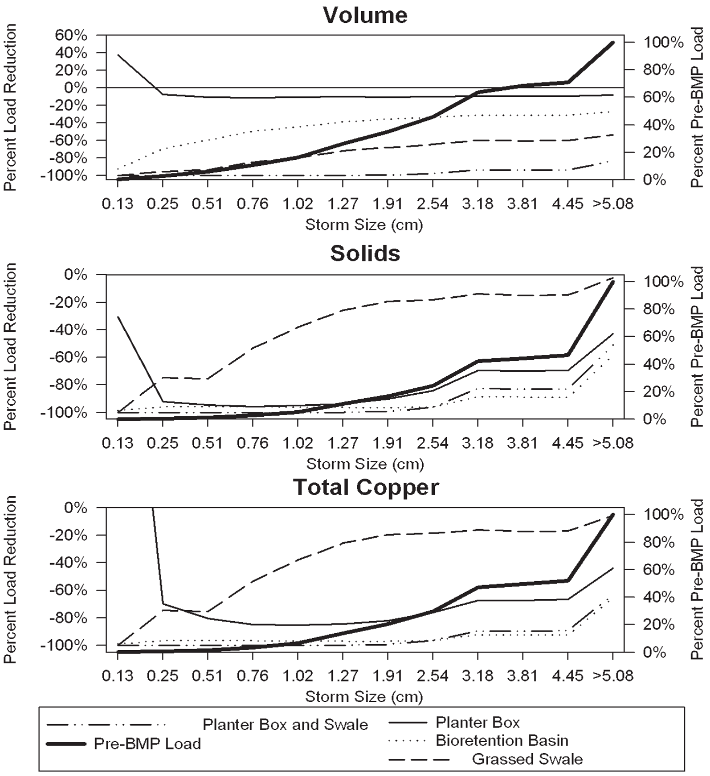

Figure 5. Cumulative load for the high density residential catchment without application of any BMPs (dark line) and load reductions for each BMP scenario by storm size.

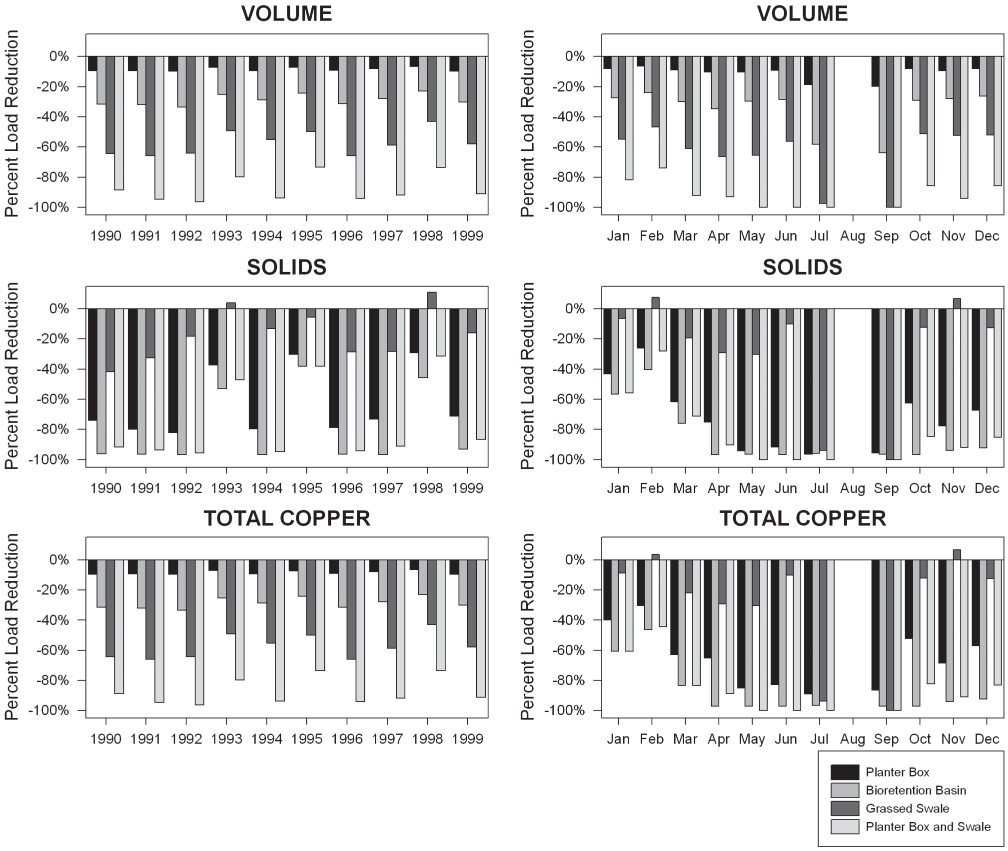

Figure 6. Percent load reduction by water year (graphs on the left) and month (graphs on the right).

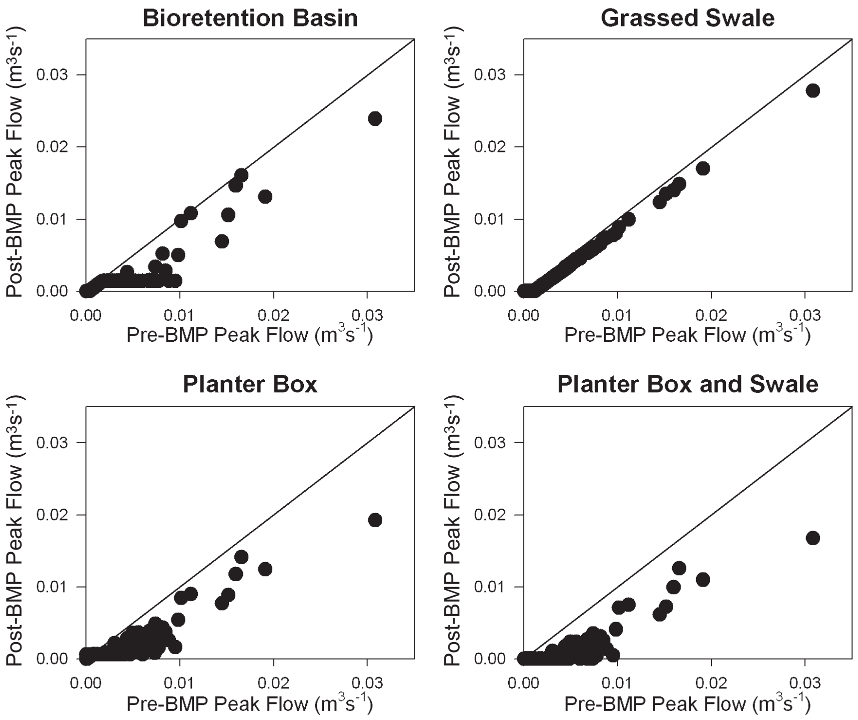

Figure 7. Reductions in peak flow with the implementation of BMPs. Reference line indicates level at which there would be no difference with or without the BMP.

Table 5. Monthly rainfall totals and average at the Los Angeles International Airport for Water Years 1990-99.

	Rain Total		Average storm	
Month	**(cm)**	**(in)**	**(cm)**	**(in)**
January	101.30	39.88	1.45	0.57
February	99.64	39.23	2.03	0.80
March	60.43	23.79	1.09	0.43
April	13.56	5.34	0.58	0.23
May	10.34	4.07	0.74	0.29
June	5.13	2.02	0.64	0.25
July	1.40	0.55	0.20	0.08
August	0.05	0.02	0.05	0.02
September	0.94	0.37	0.30	0.12
October	6.55	2.58	0.46	0.18
November	21.59	8.50	0.94	0.37
December	51.84	20.41	1.24	0.49

exceeded the CTR standard (based on total copper) for an average of 12.7 hours per storm, and the duration of exceedences increased with storm size (Figure 9). Addition of the bioretention basin decreased the average duration of exceedences to 4.7 hours, while the swale decreased exceedences to 4.9 hours. The planter box only decreased the exceedences time by three hours, but when used in series with the swale, reduced average exceedences to 4.4 hours.

Sensitivity Analyses

The effect of various factors on BMP performance varied by parameter. The bioretention basin and grassed swale simulations were most sensitive to the mechanisms associated with volumetric changes and loss rates. For example, ±25% changes in the size of the bioretention basin (and hence the retention time) had moderate changes (±5%) in volume but greater impact on the sediment and copper loads (Tables 6 and 7). The same changes in the grassed swale dimensions (length and width) had about ±15% changes in volume but little impact on the pollutant loads with respect to width and slightly a lesser change in with respect to length. Performance of the retention facilities was heavily influenced by infiltration rates of the underlying soil. Finally, small changes in degradation rates (±25% and a negative log change)

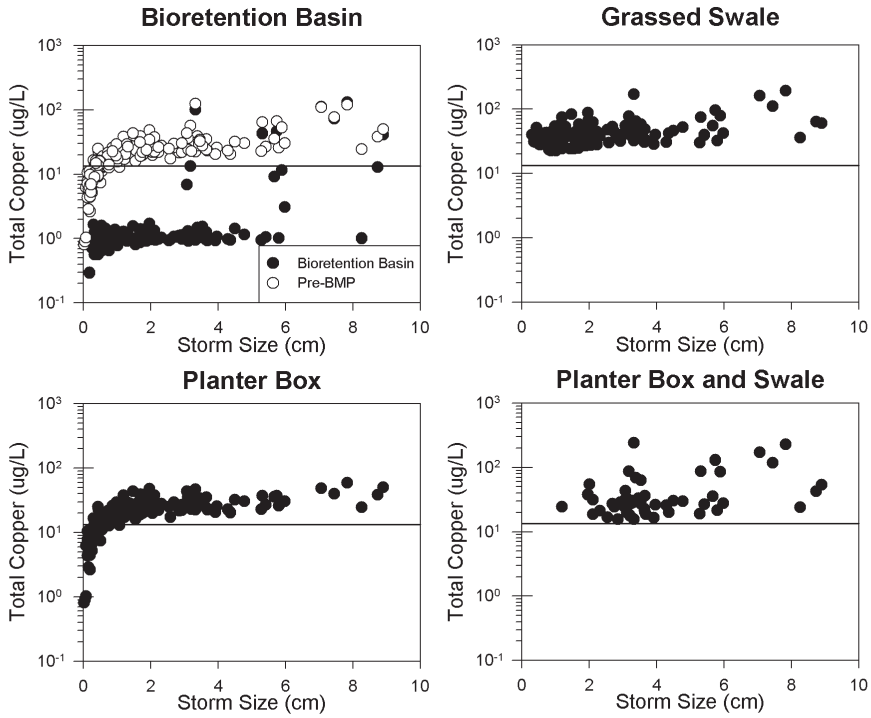

Figure 8. Total copper storm EMCs for the four BMP scenarios. The horizontal line is the CTR standard for a hardness of 100 mg/L and a resultant acute copper toxicity of 13.4 µg/L. EMCs for the land use parcel without any BMPs are shown in the top left graph only for reference (open symbols).

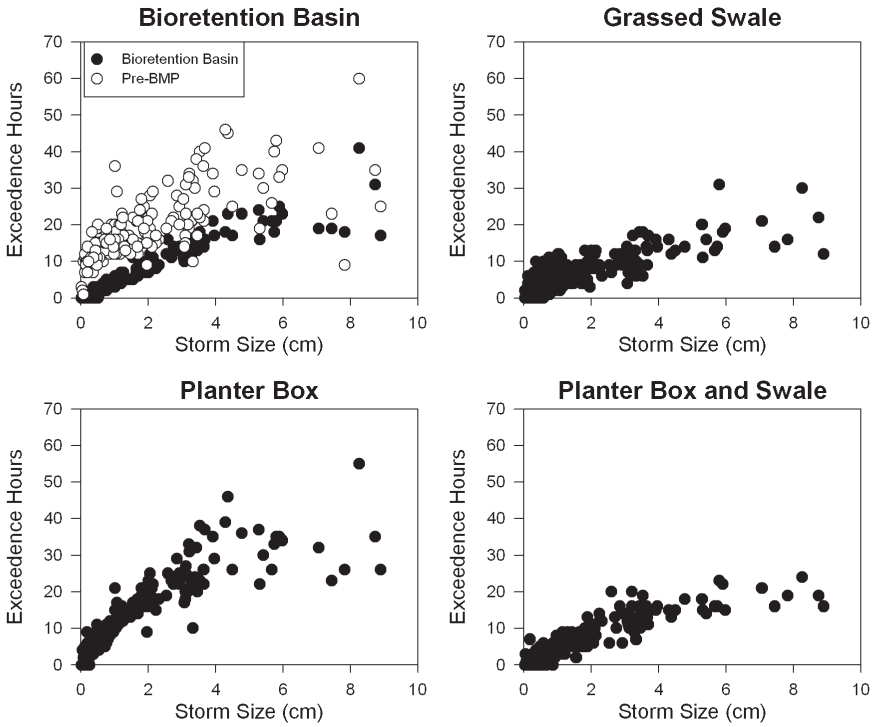

Figure 9. Exceedence hours (CTR standard, hardness = 100 mg/L, acute toxicity = 13.4 µg/L) of copper for the effluent from the four BMP scenarios. EMCs for the land use parcel without any BMPs are shown in the top left graph only for reference (open symbols).

Table 6. Bioretention basin model sensitivities on effluent volume and loads, and on copper exceedences. A negative load equals a removal by the BMP. Numbers in parenthesis are the model value.

Parameter and Model Value	Sensitivity Value	Percent Change in Load			Copper Exceedence
		Volume	Sediment	Copper	
Size (4000 m^2)	-25%	5.9%	48.5%	51.9%	18.6%
	+25%	-5.4%	-32.1%	-31.3%	-13.8%
Infiltration rate (2.54 cm/hr)	1.02	-22.5%	38.2%	47.3%	82.9%
	1.52	-8.9%	23.7%	28.3%	35.3%
	1.91	-3.9%	13.9%	16.1%	17.3%
	3.18	1.7%	-12.0%	-12.7%	-7.8%
	3.56	2.1%	-18.5%	-19.2%	-10.6%
Soil depth (0.76 m)	-25%	0.0%	0.0%	0.0%	0.0%
	+25%	0.0%	0.0%	0.0%	0.0%
Underdrain depth (0.61 m)	-25%	0.0%	0.0%	0.0%	0.0%
	+25%	0.0%	0.0%	0.0%	0.0%
Background infiltration rate (0.51 cm/hr)	-25%	7.9%	0.4%	0.4%	5.8%
	+25%	-7.4%	-0.4%	-0.4%	-6.1%
Degradation rate (Solids 1.4/hr) (Copper 0.5/hr)	- 1 log unit	0.0%	1.5%	0.5%	0.0%
	-25%	0.0%	-1.9%	-0.5%	0.0%
	+25%	0.0%	6.4%	2.3%	0.0%
	+1 log unit	0.0%	-44.7%	-19.5%	0.0%
Underdrain removal (Solids 95%) (Copper 96%)	80%	0.0%	16.3%	24.8%	0.0%
	99%	0.0%	-4.3%	-4.6%	0.0%

had little impact on the pollutant load reductions. In contrast large changes had a significant impact.

DISCUSSION

This study demonstrated that process-based modeling can be an effective approach for assessing the performance of a BMP, or series of BMPs, throughout the course of a storm. However, without additional calibration and validation, we cannot make definitive conclusions about the overall model accuracy. We have confidence in the input parameters to the BMP model because they were taken from

Table 7. Grassed swale model sensitivities on effluent volume and loads, and on copper exceedences. A negative load equals a removal by the BMP. Numbers in parentheses are the model value.

Parameter and Model Value	Sensitivity Value	Percent Change			Copper Exceedence
		Volume	Sediment	Copper	
Slope (0.05)	-25%	-1.70%	-5.00%	-5.00%	0.10%
	25%	0.80%	5.20%	5.20%	8.70%
Width (1.8 m)	-25%	15.80%	2.30%	4.10%	11.30%
	25%	-14.70%	-6.10%	-7.00%	9.40%
Length (122 m)	-25%	18.80%	11.20%	12.40%	15.90%
	25%	-15.40%	-10.10%	-11.00%	0.90%
Infiltration rate (1.8 cm/hr)	-25%	21.20%	7.60%	8.90%	10.50%
	25%	-16.80%	-7.10%	-8.20%	-6.30%
Soil depth (1.22 m)	-25%	0.00%	0.00%	0.00%	0.00%
	25%	0.00%	0.00%	0.00%	0.00%
Degradation rate (Copper 0.7/hr) (Solids 0.7/hr)	-1 log unit		2.7%	2.7%	0.0%
	-25%		0.8%	0.8%	0.0%
	+25%		-0.8%	-0.8%	0.0%
	+ 1 log unit		-23.2%	-23.2%	0.0%

a calibrated and validated runoff model (Ackerman and Weisberg 2006). Output from the BMP model was compared to the best available data from the scientific literature, which provides a general picture of the performance of the BMPs and allows for a "loose" calibration of the BMP module. Although the BMP module performed well relative to the available literature values, the paucity of data detailing the BMP design, influent and effluent concentrations, rainfall during monitored events, and information on antecedent conditions precluded a true validation. Even with this shortcoming, the BMP module provided insight into the relative effects of different design, climatic, and implementation considerations on the performance of the BMP and, therefore, proved to be a useful analytical tool.

The model enabled performance to be investigated based on a variety of endpoints, such as load reduction, effluent concentration, and frequency of exceedence of water quality standards. In general, performance was comparable based the various evaluation endpoints. However, the sensitivity of each endpoint varied. For example predicted effectiveness based on frequency of EMC exceeding standards decreased more rapidly with increasing storm size than did effectiveness based on load reduction. Although not tested in this study, differences might also be expected based on washoff rate from the land use parcel or initial condition of the BMP (e.g., how full the bioretention basin was at the start of a storm). Such differences should be accounted for when selecting an evaluation endpoint.

The BMP simulations demonstrate not only that water quality impacts can be mitigated but also that peak stormwater runoff can be decreased. The models showed that peak flows and storm volumes decreased under all BMP scenarios. However, changes in the timing of discharge from the site were not evaluated. Previous studies (Roesner and Bledsoe 2003) have shown that both magnitude and duration of flow are important factors to consider for evaluation of downstream effects. This should be evaluated in future work.

The ranges of predicted effectiveness based on this modeling exercise were slightly larger than those reported in the literature or in the BMP database. This is not unexpected given the range of conditions evaluated by the model. In contrast within a small range of conditions (e.g., storm sizes), the model provides a more precise evaluation of effectiveness (i.e., a narrower range of values). This dichotomy illustrates 1) that literature derived values must be used with caution unless the exact conditions (and antecedent conditions) under which they were obtained is well understood, and 2) that the model can be a useful tool to help better understand the effect of various factors (e.g., storm size, BMP size) on expected performance.

Any model application is only as good as the data underlying its development. The majority of the input data for the bioretention basin and grassed swale were obtained from the International Stormwater BMP database (www.bmpdatabase.org), and were typically based on runoff from a transportation-related activity (road, parking lot, etc). These values may or may not be representative of runoff from other areas (e.g., high density residential). The data from the literature review (Table 2) showed a higher removal rate than the data from the BMP database (Figure 2). The differences between the two data sources may be due to a variety of factors, such as 1) the source of the runoff sampled, e.g., particulates from transportation sources could have a different size distribution than other sources resulting in different removal rates for particle-bound copper and solids and bound copper would thus have a different removal rate, 2) the geographic location investigated, e.g., most literature data is from the Eastern U.S. while data from the BMP database are

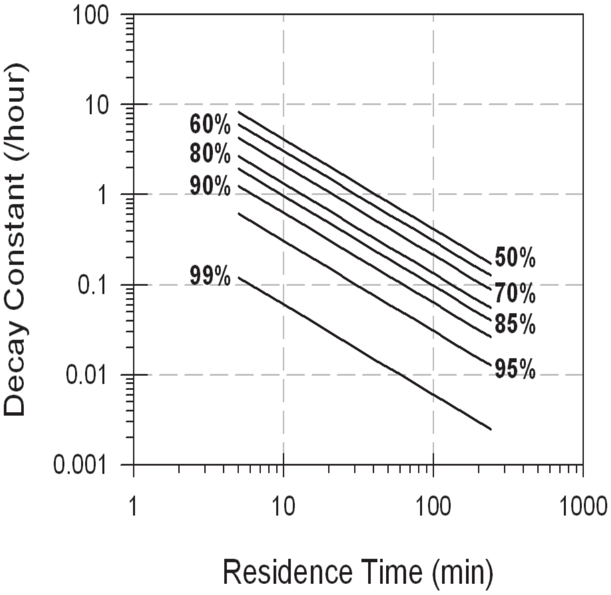

Figure 10. The relationship between residence time, decay rate, and percent removal for the first order decay rate equation. Lines indicate percent removal realized for a given decay rate constant and residence time.

from the Western U.S. which had very different rainfall patterns, 3) differences in the size or type of storms sampled, or 4) differences in the specific design specifications of the BMP type sampled, e.g., a bioretention basin sampled by each study could have different residence times or infiltration rates. As shown in this study, each of these factors can influence the ultimate performance of the BMP.

Another critical component to an accurate model is careful attention to the processes described by the model and the assumptions employed in their application. The sensitivity analyses have shown that the bioretention basin and the grassed swale are most sensitive to changes in the water balance in the BMP. These sensitivities highlight that the design and performance objectives of a BMP need to be thoroughly identified and evaluated before their implementation. For example, changing the infiltration rate in a bioretention basin can change the residence time in the surface storage, and with a consistent decay rate, have a large effect on the pollutant removal (Figure 10). In contrast, small changes in assumptions about decay rate have only a modest effect on predicted performance

The available data allowed for only a general calibration of the model. One aspect of the modeling that could be improved is including pollutants in both dissolved and particulate forms. Data supporting the HSPF validation model (Ackerman and Weisberg 2006) only included total pollutants (i.e., combination of dissolved and particulate phase); therefore, only the effect of BMPs on total metals could be modeled with confidence. The model could also be improved with the collection of additional data (field and/or laboratory) to better calibrate and, more significantly, validate the BMP model. An independent data set that the model can be tested against should be collected to ensure that the model parameters, most significantly the decay and percent removal, are accurate. For example, in the model the infiltration rate, regardless of BMP type can have a significant impact on the pollutant removal (Tables 6 and 7). In addition, time variable concentration data at both the BMP inlet and outlet would provide an opportunity for model validation.

This model is an excellent step in advancing the application and understanding of BMPs and their impact on stormwater runoff. It allows for the BMPs to be evaluated over a wide range of storms that would be difficult to monitor empirically. It also can be used to assess the limits of the BMPs, which can enable better BMP design and implementation. Additional information needs to be gathered to further enhance the model and understand the dynamics within a BMP. Information on particle dynamics in the catchment runoff as well as the fractionation of pollutants during a storm must be collected to have good information feeding into the BMP model. Additionally, data on BMP performance at a variety of locations with differing land uses should be collected. Furthermore, there needs to be follow on sampling of those locations to see how the BMP performance changes with age, storm size, as well as cumulative rainfall throughout the storm season.

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