TECHNICAL MEMORANDUM

Summary of Biofilter Effectiveness from Local and National Data Sets

Prepared for

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July 25, 2006

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Introduction

To support ongoing stormwater planning and design efforts, Seattle Public Utilities is interested in compiling data on the efficiency of different types of best management practices (BMPs) for water treatment. Of particular interest are performance data for two types of biofilters: bioswales and bioretention systems. A *bioswale* is a structural BMP that is designed to collect, convey, and promote the infiltration of stormwater within a trapezoidal channel that is approximately 100 to 200 feet long (Horner et al. 1994). Stormwater moving through surface flow paths within the bioswale is filtered through surface vegetation and the top few centimeters of soil. Although bioswales are designed to convey surface water, they have been shown to result in the infiltration of approximately 40 percent of inflowing stormwater (Strecker et al. 2004). Conversely, bioretention systems (hereafter referred to as *rain gardens*) are designed to result in the infiltration of 100 percent of inflowing stormwater up to the system's design storm size. They are typically designed as shallow depressions in the landscape, planted with trees or shrubs, and amended with mulch. Stormwater is routed into the depression and allowed to infiltrate the soil into ground water or to a subsurface drain.

This memorandum documents the removal efficiency of three types of bioswales (i.e., grass swales, wetland swales, and dry swales with underdrains) and rain gardens for the following pollutants of concern that are commonly found in urban stormwater: total suspended sediment, total phosphorus, total zinc, petroleum hydrocarbons (e.g. oil and grease), and fecal coliform bacteria (e.g., *Escherichia coli*). Water quality data were compiled during a review of literature from local and national sources, which are described in the section "Methods," along with the procedures used to analyze the associated data. The estimates of removal efficiency for bioswales and rain gardens are presented in the section "Results," and the major findings of this literature review are summarized in the section "Conclusions."

Methods

This assessment of the effectiveness of biofilters in the Pacific Northwest is based on a review of existing literature and databases. The primary source of information related to the effectiveness of BMPs is the International Stormwater Best Management Practices Database (ISBMPD) (Moeller 2006). However, little information on local BMPs is presented in this database. Consequently, additional information was collected from a variety of local sources to augment the data from the ISBMPD. Local sources include reports commissioned by King County, the City of Portland, and the Washington State Department of Transportation (WSDOT).

The analyses performed for this BMP assessment included only data from studies that reported both influent and effluent stormwater concentrations. Because pollutant removal efficiency is strongly influenced by influent concentrations, studies that report the percentage of removal without including the influent concentrations can be misleading. Ideally, the treatment performance of a BMP should not be evaluated solely on the basis of the percentage of removal for a particular parameter (Schueler 1996). The goal of this analysis was to develop empirically based equations using regression analysis to describe removal efficiency as a function of influent pollutant concentrations. However, the development of an empirically based regression equation requires sufficient data across a range of influent concentrations. Sufficient data were available to develop regression equations for all the BMPs analyzed except wetland bioswales.

Mean concentrations of stormwater pollutants in influent and effluent across a range of events were used to calculate removal efficiencies. If a study did not compare the pollutant concentrations in at least three influent and effluent samples, it was not used. When calculating pollutant removal efficiencies, only concentrations were considered. Calculating pollutant removal efficiency using loads is another method that was not used in this assessment. In BMPs that result in the infiltration of stormwater, load removal is frequently very high. An analysis of concentrations without consideration of mass removal through infiltration results in worst-case removal efficiencies. The procedural steps for developing the regression analysis approach were as follows:

1. Data from existing studies of BMPs were compiled. Only studies that compared event mean concentrations (EMCs) in the influent and effluent for a minimum of three storms were used.
2. The mean of all the influent EMCs for a given study site was plotted against the mean of all the effluent EMCs for the same site.
3. This process was repeated for the each monitored BMP.
4. Local and national BMPs were compared and contrasted.
5. Regression analysis was performed.

Results

Estimates of pollutant removal efficiencies for three types of bioswales (grass swales, wetland swales, dry swales with underdrains) and rain gardens are presented in the following subsections.

Grass Bioswales

On average, grass bioswales in the Pacific Northwest have been observed to remove 64, 18, and 47 percent of influent total suspended sediment, total phosphorus, and total zinc, respectively (Table 1). The estimates of removal efficiency for these parameters were likely reduced by the inclusion of data from a WSDOT study of the performance of a bioswale receiving highly diluted runoff (see study No. 7 in Table 1) (WSDOT 2005). If this study is excluded from the analysis, local removal efficiencies for total suspended sediment, total phosphorus, and total zinc increase to 72, 28, and 51 percent, respectively (Table 1). These results illustrate the strong influence of influent concentration on the removal efficiency of BMPs. Of the local bioswales for which there were hydrocarbon data (three bioswales) and bacteria data (four bioswales), removal efficiency was poor, averaging -10 percent for hydrocarbons and -8 percent for bacteria.

Table 1. Pollutant concentrations in influent and effluent and the percentage of removal in 10 local grass bioswales and 15 national bioswales.

							Total Suspended Sediment (mg/L)			Total Phosphorus (mg/L)			Total Zinc (µg/L)			Hydrocarbons (mg/L)			Bacteria (colonies/100 mL)			
No.	Reference	State	Year	No. of Samples	Slope (percent)	Length (feet)	Inlet	Outlet	Percent Removal	Inlet	Outlet	Percent Removal	Inlet	Outlet	Percent Removal	Inlet	Outlet	Percent Removal	Inlet	Outlet	Percent Removal	Notes
Pacific Northwest Bioswales																						
1	Moeller (2006)	WA	1991–1993	8		570	42.1	14	67	0.194	0.206	-6	57.4	31.2	46	0.247	0.401	-62	-	+		Reported increase in fecal coliform bacteria
2	Moeller (2006)	OR	2001	9	2.3	160	105.8	30.3	71	0.380	0.300	21	169.3	64	62	7.5	6.5	13	11,789	10,324	12	Bacteria = *E. coli*
3	Moeller (2006)	OR	1999–2000	6			192	107.6	44	0.393	0.305	22	192.8	78.6	59							Residence time = 8 to 13 minutes
4	Moeller (2006)	OR	1999–2001	6			126	27.9	78	0.393	0.318	19	192.8	68.8	64%							Residence time = 8 to 13 minutes
5	Moeller (2006)	OR	2001–2002	6	0.2	210	192	21	89	0.099	0.094	5	17.05	17.4	-2							
6	Moeller (2006)	OR	2001	9	2.3	160	109.5	33.4	69	0.360	0.260	28	170.3	64.2	62	7.5	6	20	11,789	11,145	5	Bacteria = *E. coli*
7	WSDOT (2005)	WA	2003–2005	15			5	5	0	0.03	0.05	-67	20	17	15							
8	ACWA (2006)	OR		6			108.2	18.4	83	0.227	0.05	78	132.8	29.2	78							
9	Kulzer and Horner (1992)	WA	1992			100	150	60	60	0.133	0.06	55	71.4	60	16				8.6	10.75	-25	Bacteria = fecal coliform
10	Kulzer and Horner (1992)	WA	1992			200	82.4	14	83	0.197	0.14	29	82	23	72				3,176	3,970	-25	Bacteria = fecal coliform
Average of 1-10							111.3	33.16	64	0.241	0.178	18	110.6	45.3	47	5.1	4.3	-10	6,691	6,362	-8	
Average of 1-6,8-10 (7 excluded)							123.1	36.3	72	0.26	0.19	28	120.7	48.5	51	5.1	4.3	-10	6,691	6,362	-8	
National Bioswales																						
1	Barrett (2005)	National	1991–2005	14 bioswales (various slopes and lengths)			53	30	43	0.26	0.48	-88	101	47	53							
2	Moeller (2006)	MN	1991–2005	1 bioswale (length and slope not reported)												18.8	5	73	9,000	10,000	-13	

Notes: Physical characteristics of the bioswale are described if available.
For the most accurate representation of local bioswale removal efficiency, the regression equations from Figures 1–3 should be used.
µg/L = micrograms per liter.
mg/L = milligrams per liter.
mL = milliliters.

Nationally, bioswales have not performed as well as they have in the Pacific Northwest. Averaging the results for 14 grass bioswales, Barrett (2005) reported removal efficiencies for total suspended sediment, total phosphorus, and total zinc of 43, -88, and 53 percent, respectively (Table 1). Outside of the Pacific Northwest, only one study quantifying the removal of hydrocarbons and bacteria in grass bioswales could be found. This national study reported 73 percent hydrocarbon removal and -13 percent bacteria removal. It should be noted that the influent hydrocarbon concentration in this study was more than twice as high as the highest influent concentration observed in local studies, which helps to explain the discrepancy between the hydrocarbon removal results for local grass bioswales and the results for this national grass bioswale (location not reported by Barrett [2005]).

When comparing the efficiencies of local and national bioswales at removing total suspended sediment, the local bioswales generally perform better across the majority of influent concentrations (Figure 1). For example, at low concentrations of influent total suspended sediment, bioswale performance across various regions is indistinguishable. However, as influent concentrations increase, bioswales in the Pacific Northwest seem to perform better than bioswales in other areas of North America (Figure 1).

Differences between regional and national data are more dramatic when assessing the removal of total phosphorus. Specifically, the ISBMPD reports that grass bioswales across the country tend to act as sources of total phosphorus, whereas all but two of the local grass bioswales acted as sinks for total phosphorus (Figure 2).

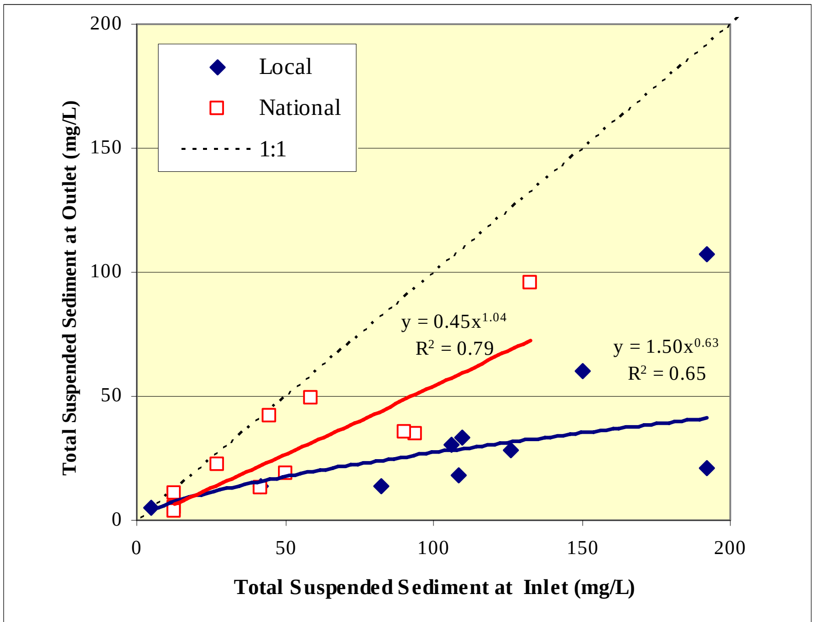
Both the swales in the Pacific Northwest and the swales from across the nation performed moderately well at removing total zinc when influent concentrations were elevated. The removal efficiencies for total zinc did not differ substantially between the local and national grass bioswales, with all the swales removing between 0 and 60 percent of influent zinc (Figure 3).

For each pollutant addressed in this report, removal efficiencies improved with increasing influent concentration. This can be gauged by measuring the distance from the regression line to the 1:1 line in Figures 1 through 3 (i.e., the farther below the 1:1 line, the greater the removal). If the regression line and the 1:1 line are parallel, the removal efficiency is equal across all influent concentrations. This is nearly the case for total phosphorus (see Figure 2). The regression equations for the local grass bioswales (see Figures 1 through 3) can be used to estimate pollutant removal for any influent concentration. For example, the regression equation for the removal of total suspended sediment is the following:

$$y = 1.5x^{0.63}$$

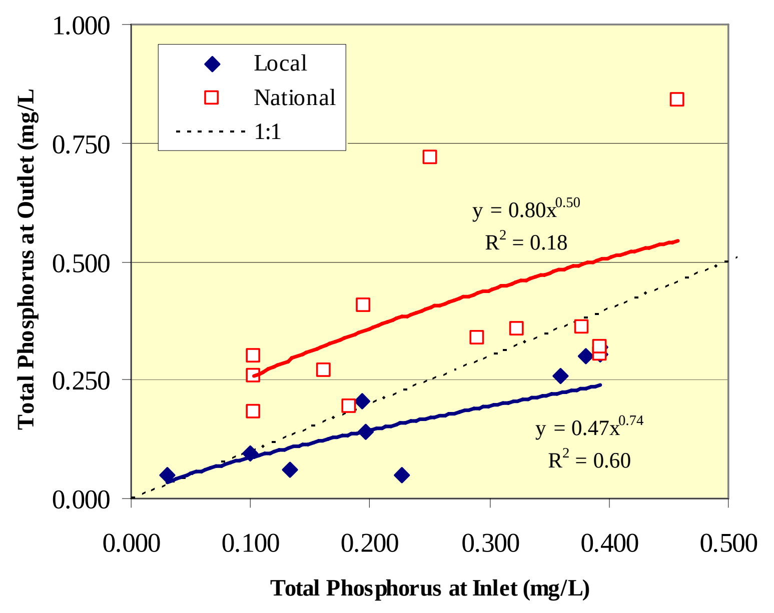
where: x = influent concentration
y = expected effluent concentration

If the influent concentration is 100 milligrams per liter (mg/L), the effluent can be expected to be approximately 27 mg/L, a 73 percent reduction. Conversely, if the influent concentration is only 20 mg/L, the expected effluent concentration would be 9.9 mg/L, only a 50 percent reduction. In



Note: A data point below the dotted 1:1 line indicates retention of phosphorus by the bioswale; a data point above the line indicates phosphorus export.

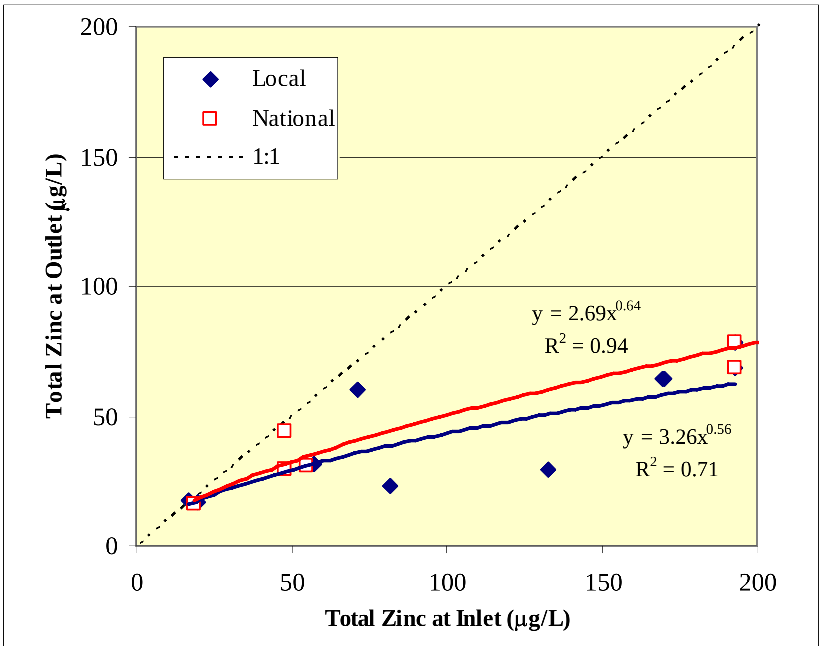
Figure 1. **Mean concentrations of total suspended sediment measured at the inlets and outlets of 10 grass bioswales in the Pacific Northwest and 11 grass bioswales across North America.**



Note: A data point below the dotted 1:1 line indicates retention of phosphorus by the bioswale; a data point above the line indicates phosphorus export.

Figure 2. **Mean concentrations of total phosphorus measured at the inlets and outlets of 10 grass bioswales in the Pacific Northwest and 14 grass bioswales across North America.**

the case of the grass bioswales, nonlinear regression equations were used. Due to a few high-leverage data points, linear fits tended to cross the *x* axis at values greater than zero. This is an inaccurate model for grass bioswale performance at low concentrations, as it would indicate that for a range of low influent concentrations, effluent concentrations will be zero. Because no BMP can reduce effluent concentrations to zero, an exponential fit was chosen as a more accurate model of BMP performance. These regression equations likely represent a more accurate empirical quantification of local grass bioswale performance and their use in local management/planning decisions is recommended.



Note: A data point below the dotted 1:1 line indicates retention of phosphorus by the bioswale; a data point above the line indicates phosphorus export.

Figure 3. Mean concentrations of total zinc measured at the inlets and outlets of 10 grass bioswales in the Pacific Northwest and eight grass bioswales across North America.

Wetland Bioswales

Data related to removal efficiencies for wetland bioswales were limited. Four wetland bioswales were assessed, one local (Koon 1995) and three from the ISBMPD (Moeller 2006). The BMP category within the ISBMPD is titled "Wetland-Channel with Wetland Bottom," and includes a variety of BMPs, some with characteristics more similar to a wetland and some designed to be more like a swale. Consequently, each of the BMP designs had to be scrutinized and only the swale-type was included in this analysis. The local wetland bioswale removed 43, 24, and 20 percent of total suspended sediment, total phosphorus, and total zinc, respectively (Table 2). On average, the three national wetland bioswales removed 77, 47, and 68 percent of influent total suspended sediment, total phosphorus, and total zinc, respectively. With only one local site, it is difficult to compare the local and national data; however, it appears that wetland bioswales may be more effective than grass bioswales at removing total phosphorus.

Dry Bioswales with Underdrains

There are no available data on these swale designs. Processing is complex in such systems as there are two treatment paths though the BMP. Stormwater may pass through the soil matrix into the underdrain, or water may move through surface and hyporheic pathways before passing through an exit weir. Surface water treatment would be similar to that in a grass bioswale, whereas infiltrated water treatment would be more similar to that in an infiltration berm. For the purpose of this report it has been assumed that most of the stormwater moving through a dry bioswale with an underdrain would exit through the underdrain and that infiltration berm pollutant removal data can be used as a surrogate for dry swale with underdrain data.

Structural BMPs that increase the amount and duration of contact between a soil (inorganic or organic) matrix tend to perform better than BMPs that rely on dilution and processing by water-column settling (i.e. wet ponds). Two types of local BMPs were included in this analysis: compost-amended vegetated filter strips (CAVFS) and ecology embankments. These BMPs were designed with either underdrains (ecology embankments) or percolation trenches (CAVFS). Therefore, the hydraulics should be similar to a dry swale with an underdrain. Nationwide data on filter strips were obtained from Barrett (2005) and used for comparison.

There is not a substantial difference between removal efficiencies in local and national filter strips (Table 3). For example, local filter strips remove 78, 25, and 73 percent of influent total suspended sediment, total phosphorus, and total zinc, respectively. National filter strips remove 72, 24, and 75 percent of the same pollutants. Figures 4 and 6 also indicate that there is not a substantial difference between removal efficiencies for total suspended sediment and total zinc in the local and national data.

However, Figure 5 shows that local filter strips are more effective at removing total phosphorus than their national counterparts. This was not reflected in the Table 3 averages because low influent concentrations at local BMP (number 3) contributed to very poor treatment performance (a removal efficiency of -91 percent) which, in turn, reduced the overall average for local systems. Figure 5 indicates that at higher influent concentrations of total phosphorus, local filter strips perform better than the national filter strips. It should be noted that the regression equations in Figures 4 through 6 are based on only four data points and there is a large residual error. Therefore, more data are needed to improve the accuracy of these equations.

Rain Gardens

Like filter strips, rain gardens maximize the contact time between stormwater pollutants and the soil matrix. The few data that exist indicate that rain gardens are very effective at removing pollutants. The primary difficulty in collecting data from rain gardens is that they are designed for water infiltration. Therefore, there is no easy way to sample stormwater exiting these BMPs. This, combined with the fact that rain gardens have only recently become a popular BMP choice, has resulted in a paucity of performance data. There are no available data on local rain garden performance. Table 4 and Figures 7 through 9 present data from two separate studies in Maryland (Davis et al. 2001, 2006, 2003) and Minnesota (Tornes 2005).

Table 2. Pollutant concentrations in influent and effluent and the percentage of removal in one local wetland bioswale and one wetland bioswale in Minnesota.

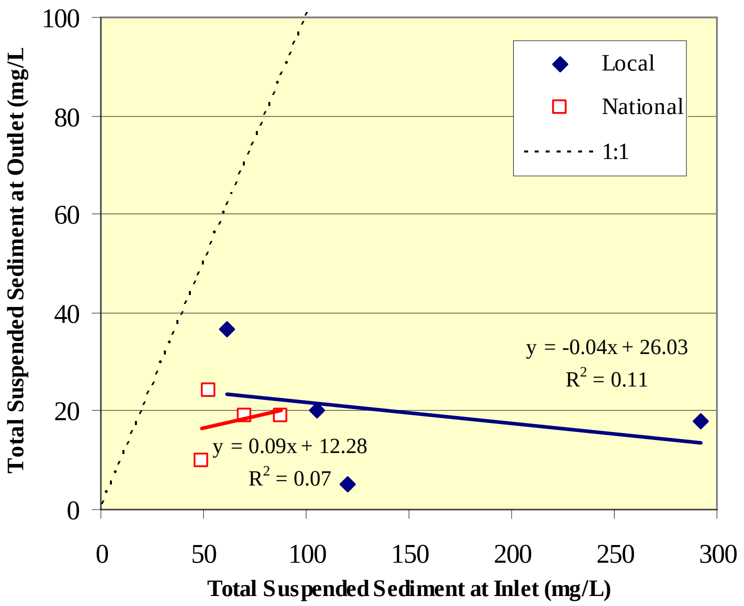
No.	Reference	State	Year	No. of Samples	Slope	Length	Total Suspended Sediment (mg/L)			Total Phosphorus (mg/L			Total Zinc (µg/L)		
					(percent)	(feet)	Inlet	Outlet	Percent Removal	Inlet	Outlet	Percent Removal	Inlet	Outlet	Percent Removal
Pacific Northwest—Wetland Vegetation															
1	Koon (1995)	WA	1994–1995	15	1.1	350	30.3	17.2	43	0.097	0.074	24	21	16.8	20
National Swales—Wetland Vegetation															
1	Moeller (2006)	National	1992–2005	3 BMPs	Various	Various	124.7	28.9	77	0.43	0.23	47	103	32.6	68

Note: Physical characteristics of the bioswale are described if available.
BMP = best management practice.
µg/L = micrograms per liter.
mg/L = milligrams per liter.

Table 3. Pollutant concentrations in influent and effluent and the percentage of removal for four local vegetated filter strips and four national vegetated filter strips.

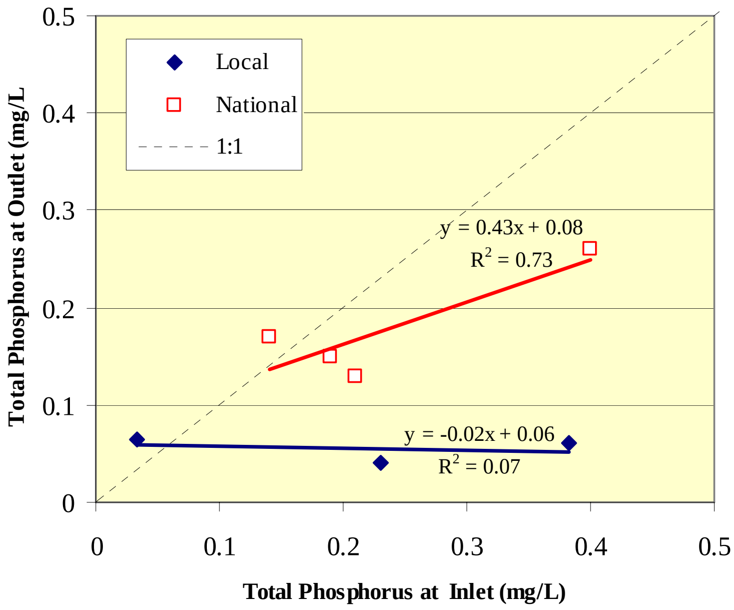
No.	Reference	State	Year	No. of Samples (Right?)	Filter Type	Total Suspended Sediment (mg/L)			Total Phosphorus (mg/L)			Total Zinc (µg/L)		
						Inlet	Outlet	Percent Removal	Inlet	Outlet	Percent Removal	Inlet	Outlet	Percent Removal
Pacific Northwest Vegetated Filter Strips														
1	WSDOT (2005)	WA	2003–2005	15	CAVFS	105	20	81	ND	ND	ND	110	25	77
2	WSDOT (2005)	WA	2003–2005	15	EE	120	5	96	0.23	0.04	83	400	30	93
3	ACWA (2006)	WA	ND	8	CAVFS	61.4	36.6	40	0.034	0.065	-91	67.4	45.4	33
4	WSDOT (2005)	WA	2005–2006	6	CAVFS	292	18	94	0.383	0.06	84	278.7	33.8	88
Average of local BMPs						144.6	19.9	78	0.216	0.055	25	214	33.6	73
National Vegetated Filter Strips														
1	Barrett (2005)	National	1991–2005	4 BMPs	Filter strip	65	18	72	0.235	0.1775	24	88.5	22	75

Notes: Physical characteristics of the filter strip are described if available.
For the most accurate representation of local bioswale removal efficiency, the regression equations from Figures 1–3 should be used.
CAVFS = compost-amended vegetated filter strip (Herrera 2005).
BMP = best management practice.
EE = ecology embankment (Herrera 2006).
µg/L = micrograms per liter.
mg/L = milligrams per liter.



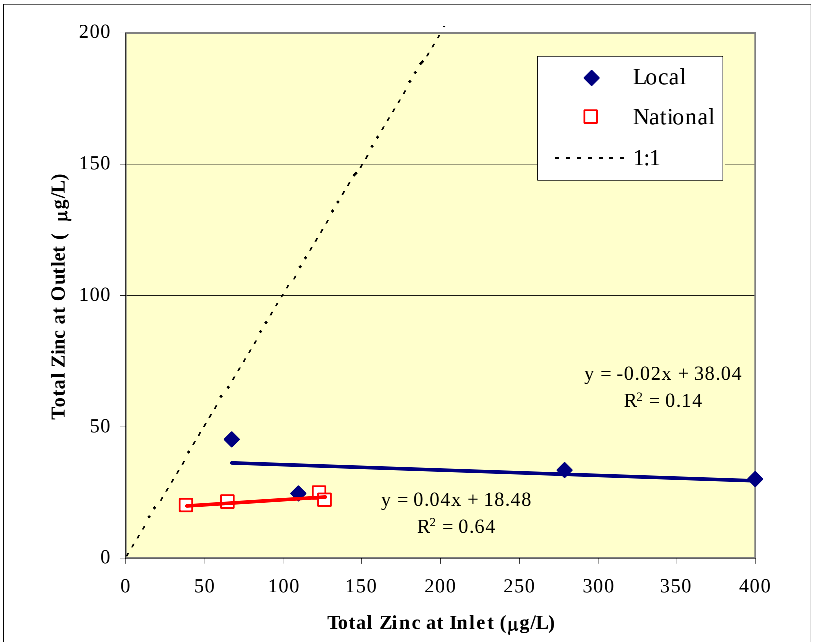
Note: A data point below the dotted 1:1 line indicates retention of phosphorus by the bioswale; a data point above the line indicates phosphorus export.

Figure 4. **Mean concentrations of total suspended sediment measured at the inlets and outlets of four vegetated filter strips in the Pacific Northwest and four vegetated filter strips across North America.**



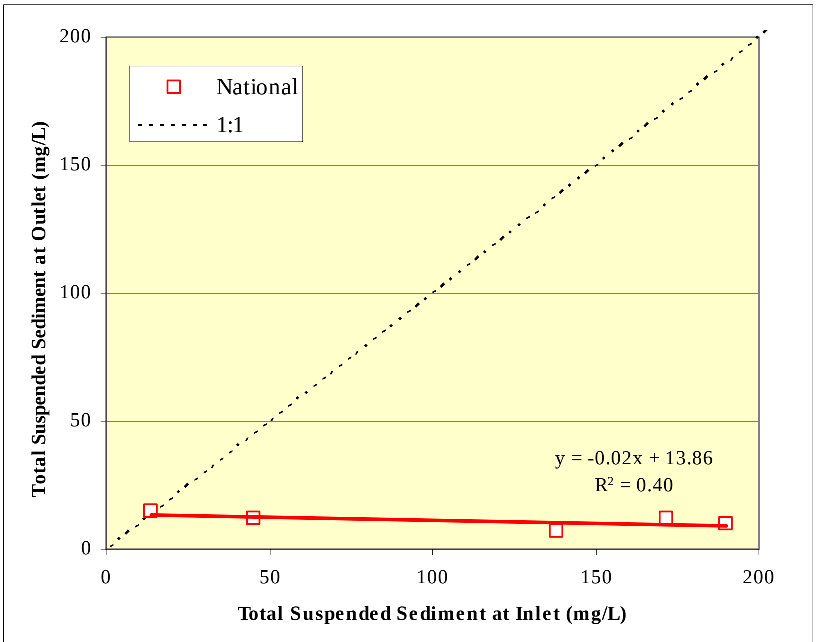
Note: A data point below the dotted 1:1 line indicates retention of phosphorus by the bioswale; a data point above the line indicates phosphorus export.

Figure 5. **Mean concentrations of total phosphorus measured at the inlets and outlets of four vegetated filter strips in the Pacific Northwest and four vegetated filter strips across North America.**



Note: A data point below the dotted 1:1 line indicates retention of phosphorus by the bioswale; a data point above the line indicates phosphorus export.

Figure 6. **Mean concentrations of total zinc measured at the inlets and outlets of four vegetated filter strips in the Pacific Northwest and four vegetated filter strips across North America.**



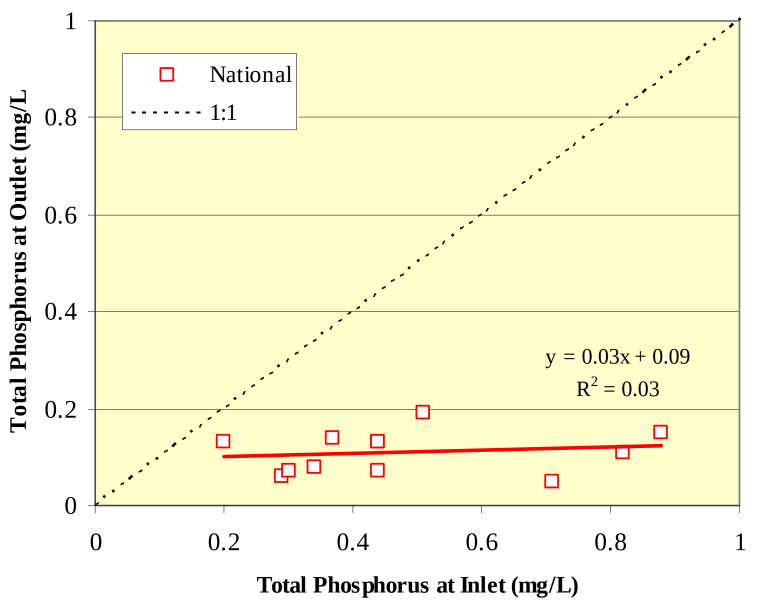
Note: A data point below the dotted 1:1 line indicates retention of phosphorus by the bioswale; a data point above the line indicates phosphorus export.

Figure 7. **Mean concentrations of total suspended sediment measured at the inlets and outlets of five rain gardens in Minnesota.**

Table 4. Pollutant concentrations in influent and effluent and percentage of removal in rain gardens and one laboratory column experiment.

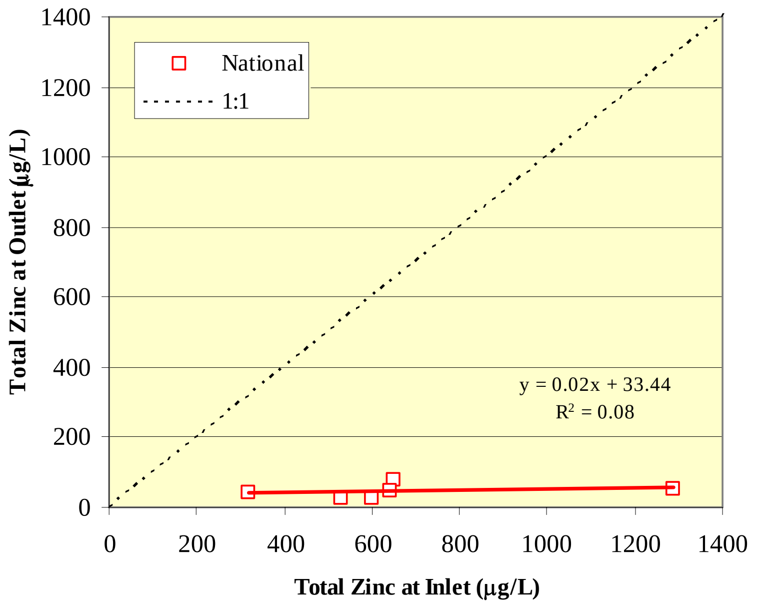
No.	Reference	State	Year	No. of Samples	Total Suspended Sediment (mg/L)			Total Phosphorus (mg/L)			Total Zinc (µg/L)			Notes
					Inlet	Outlet	Percent Removal	Inlet	Outlet	Percent Removal	Inlet	Outlet	Percent Removal	
National Rain Gardens														
1	Davis et al. (2003)	MD	1999	5				0.51	0.19	63	530	25	95	Deep mulch layer
2	Davis et al. (2003)	MD	1999	3				0.82	0.11	87	1100	390	65	Minimal compost mulch in design
3	Davis et al. (2003)	MD	1999	12				0.44	0.13	70	650	78	88	Lab experiment flow rate = 8.1 cm/hr
4	Davis et al. (2003)	MD	1999	12				0.44	0.07	84	640	46	93	Lab experiment flow rate = 2.0 cm/hr
5	Davis et al. (2003)	MD	1999	12				0.88	0.15	83	1290	53	96	Lab experiment high concentration
6	Davis et al. (2003)	MD	1999	12				0.37	0.14	62	320	43	87	Lab experiment low concentration
7	Davis et al. (2001)	MD	1999	12				0.44	0.13	70	600	25	96	Lab, median concentration, 4.1 cm/hr
8	Tornes (2005)	MN	2002–2004	5	190	10	95	0.29	0.06	79				
9	Tornes (2005)	MN	2002–2004	8	45.5	12	74	0.3	0.07	77				
10	Tornes (2005)	MN	2002–2004	8	14	12	14	0.2	0.13	35				
11	Tornes (2005)	MN	2002–2004	8	172	12	93	0.34	0.08	76				
12	Tornes (2005)	MN	2002–2004	8	138	7	95	0.71	0.05	93				
Average of national BMPs					111.9	12	74	0.48	0.11	73	733	94	88	

Note: The laboratory experiment was conducted under various conditions, all of which affected removal efficiency.
BMP = best management practice.
cm = centimeters.
µg/L = micrograms per liter.
mg/L = milligrams per liter.



Note: A data point below the dotted 1:1 line indicates retention of phosphorus by the bioswale; a data point above the line indicates phosphorus export.

Figure 8. Mean concentrations of total measured at the inlets and outlets of 12 rain gardens in Maryland and Minnesota.



Note: A data point below the dotted 1:1 line indicates retention of phosphorus by the bioswale; a data point above the line indicates phosphorus export.

Figure 9. Mean concentrations of total zinc measured at the inlets and outlets of seven rain gardens in Maryland.

Figures 7 through 9 indicate that rain gardens have high pollutant removal efficiencies across a wide range of influent concentrations. When taken together, the studies show that rain gardens remove 74, 73, and 88 percent of influent total suspended sediment, total phosphorus, and total zinc, respectively (see Table 4).

The Davis et al. (2001) study is of particular interest as they used laboratory column experiments to analyze the effect of hydraulic loading rate (HLR) and influent concentration on removal efficiency. High influent concentration and low HLR both produced improved removal efficiency, while high HLR and low influent concentration reduced removal efficiency. Despite this pattern, removal efficiencies were relatively high across all the treatments. Even when the HLR was 8.1 centimeters per hour, the removal of total phosphorus and total zinc was 70 and 88 percent, respectively.

A subsequent Davis et al. (2001) study examined the performance of two rain gardens in non-laboratory settings. One of these rain gardens was constructed with minimal mulch. The effect of low mulch on total zinc removal was drastic, as only 65 percent of the influent zinc was removed by the rain garden, compared with 95 percent removal in the high-mulch system. Apparently, a mulch layer (5 centimeters in the Davis et al. [2003] study) on the surface of the BMP is essential for optimal performance. Davis et al. (2001) state that "Laboratory and pilot studies have implicated the surface mulch layer as the most important component of the bioretention facility for metals removal." The low phosphorus retention in the mulched rain garden (number 1 in Table 4) may be attributed to the fact that the system was 10 years old and may have become saturated with phosphorus.

In Figures 7 through 9, the data show that rain gardens consistently exported approximately 13.9 mg/L, 0.09 mg/L, and 33.4 micrograms per liter (μg/L) of total suspended sediment, total phosphorus, and total zinc, respectively, independent of variable influent concentrations (the outlier from the low-mulch rain garden was excluded from Figure 8) . Therefore, removal efficiencies greatly increase with increasing influent concentration. Using the regression equation in Figure 9, an influent concentration of 100 μg/L would be reduced by 65 percent, while an influent concentration of 1,000 μg/L would be reduced by 95 percent.

Conclusions

The results of this assessment indicate that influent pollutant concentration is an important variable that must be considered when assessing the removal efficiency of a stormwater structural BMP. Limited data were available in the published literature documenting the removal of hydrocarbons and bacteria. However, there are a number of studies that have addressed the processing of total suspended sediment, total phosphorus, and total zinc by BMPs. For these pollutants, processing in grass bioswales was observed to be more efficient in local BMPs than in other studies across North America. There were limited local data for the other BMPs, with only one local wetland bioswale, four local biofilter strips (used as a surrogate for a dry bioswale with underdrain), and no local rain gardens. Regression equations derived through this study provide a useful means for assessing pollutant removal efficiency in various stormwater BMP facilities across a wide range of influent pollutant concentrations.

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