Performance Assessment of a Street-Drainage Bioretention System

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ABSTRACT: Event-based, flow-paced composite sampling was carried out at the inlet and outlet of a street-side bioretention facility in Seattle, Washington, to assess its ability to reduce street runoff quantity and pollutants. Over 2.5 years, 48 to 74% of the incoming runoff was lost to infiltration and evaporation. Outlet pollutant concentrations were significantly lower than those at the inlet for nearly all monitored constituents. In terms of mass, the system retained most of the incoming pollutants. Besides soluble reactive phosphorus (the mass of which possibly increased), dissolved copper was the least effectively retained; at least 58% of dissolved copper (and potentially as much as 79%) was captured by the system. Motor oil was removed most effectively, with 92 to 96% of the incoming motor oil not leaving the system. The results indicate that bioretention systems can achieve a high level of runoff retention and treatment in real-weather conditions. *Water Environ. Res.*, **82**, 109 (2010).

KEYWORDS: stormwater, runoff, bioretention, water quality monitoring, best management practices, low-impact development.

Introduction

Until 2 decades ago, stormwater management, as a discipline, was focused almost wholly on flood prevention. Downstream effects on water quality and quantity were of little concern. More recently, contamination of runoff and the physical in-stream effects of flashy urban hydrology have received attention in numerous studies (Booth and Jackson, 1997; Konrad et al., 2005; Marsalek et al., 1999; U.S. Environmental Protection Agency, 1983).

To minimize the effects of stormwater runoff from new developments, engineers traditionally have designed large, solitary retention/detention and water quality facilities. More recently, advocates of low-impact development (LID) have proposed new surface-drainage design methods. An overarching principle is to create some number of smaller systems integrated into the layout of the development, higher on the hillslope, as opposed to one centralized system located in the lowest part of the neighborhood. These systems are designed with amended organic soils intended to treat runoff as it flows through. Above-ground storage also is provided to slow water and increase contact with the amended soils. This practice, sometimes referred to as

bioretention, typically benefits from additional pollutant removal by means of infiltration to native soils.

While a number of bioretention systems have been built in a few regions of the nation, performance monitoring has been limited. There are few data for the removal of nutrients and total suspended solids (TSS) and even fewer for metals. Possibly the only published field studies that used continuous flow monitoring and flow-paced composite sampling (through at least one wet season) were carried out at a Greensboro, North Carolina, shopping mall (Hunt et al., 2006) and a planned development in Jordan Cove, Connecticut (Dietz and Clausen, 2005).

In North Carolina (Hunt et al., 2006), runoff entering and leaving the bioretention system was sampled in 10 discrete rain events. It was found that the system removed 99% of the mass of total copper, 98% of the zinc, and 81% of the lead. In the case of lead, infiltration was important, because the inlet and outlet concentrations were not actually different. The researchers also found that the system removed approximately 40% of the total nitrogen mass; and removal (or addition) of total phosphorus and soluble reactive phosphorus (or dissolved phosphorus) (SRP) depended on the type of filter media.

At the planned development in Connecticut (Dietz and Clausen, 2005), the bioretention system was equipped with underdrains, from which outlet samples were taken. Metals were below detection limits in 64% of the samples; therefore, statistics for mass removal could not be calculated reasonably. The underdrain water had 32% less total nitrogen mass than the influent water, though there was a doubling in the total phosphorus mass from the inlet to outlet, possibly as a result of leaching from the system's organic soils (it should be noted that results of monitoring systems with and without underdrains are difficult to compare, in that underdrain effluent has passed through the bioretention soil column, while discharge from a unit without underdrains likely has had only surficial soil contact).

Possibly the first published field investigation of a bioretention system was carried out in Maryland (Davis et al., 2003), but it was not conducted under real-weather conditions. Synthetically generated stormwater, with known pollutant concentrations, was applied to two bioretention cells. During a single event at each of the two sites, 15 grab samples were collected from the cells' underdrains. One of the cells exhibited a concentration reduction of at least 95% for copper, lead, and zinc. The other showed a range of reduction for these metals, from 20 to 90%. The authors suggested that the difference in performance could have been the result of filter media or the presence of vascular plants.

More recently in Maryland, another experiment (Davis, 2007) was performed in real-weather conditions, testing two bioretention systems. For 9 discrete rain events, it was estimated that the

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systems removed 77 to 83% of the influent mass of copper and 84 to 88% of the lead, while zinc was removed at a rate of 54 to 69%. More data were acquired for the removal of TSS and total phosphorus ($n = 12$). These systems reduced the mass of TSS by 54 to 59% and total phosphorus by approximately 78%. However, the researchers did not collect flow-paced composite samples, instead choosing to collect samples that were biased towards the first flush of the various rain events.

Researchers in Maryland and Norway have attempted to make up for the lack of field data by monitoring pilot bioretention systems in the laboratory (Davis et al., 2003; Davis et al., 2001; Hsieh and Davis, 2005; Muthanna et al., 2007; Sun and Davis, 2007). Copper, lead, and zinc removal in all of these studies was above 50% (and typically 90% or greater). Nutrient removal was not as consistent from study to study. Of course, it can be difficult to compare between study results, as experiments are carried out in a variety of manners. Furthermore, the monitored systems (and their contributing basins, in the case of field studies) also can differ. The characteristic common to all of these systems, both in the laboratory and in the field, is that water passing through the system is filtered, to some extent, by amended soils containing varying amounts of decomposing organic matter.

Seattle Public Utilities (SPU), which oversees street drainage in the city of Seattle, Washington, has been building bioretention systems in various residential neighborhoods since 2000. The systems are all located in built-out basins, where separated storm sewers convey runoff to fish-bearing streams (whereas much of the city is drained by combined sewers). The first systems, known locally as *natural drainage systems*, were constructed in the Piper's Creek basin in northwestern Seattle. This paper presents the results of an investigation of the performance of one such system. As a general goal, the present study attempted to determine whether a bioretention system sized to fit into the existing street right-of-way could provide adequate water quality treatment for the local basin. If so, it could serve as a prototype for new developments and older cities. Specifically, the study's objectives were to determine the following:

(1) The ability of the system to retain runoff and reduce pollutant mass loadings to Piper's Creek.

(2) The effluent quality the system can produce in relation to (a) influent quality; (b) similar bioretention facilities, as reported in other studies; and (c) the Washington State water quality criteria.

Following is a description of the system and its contributing basin and a presentation of the various technical and analytical methods used to assess system performance.

Site Description and Methods

The NW 110th Street Cascade and Its Contributing Catchment. The NW 110th Street Cascade bioretention system, the focus of this study, was designed by SPU to slow and treat runoff along 4 blocks of NW 110th Street in Seattle. Previous to construction, the road shoulder was used for parking; drainage was accomplished by means of a concrete culvert, which conveyed water quickly to a ravine containing a tributary of Piper's Creek.

Brought online in 2003, the 110th Cascade is comprised of 12 stair-stepped cells, each irregularly rectangular in planform. The system spans 275 horizontal meters from the farthest upslope inlet to the outlet (interrupted by street crossings); the vertical distance between these points is 16 m.

Where cells are not separated by road crossings, a combination overflow weir transmits water from one cell to the next. Where road crossings intervene, precast concrete manholes are located just upstream and downstream of the crossings. The manholes allow for sedimentation of larger particles and convey water to (or accept water from) the cells via 20-cm-diameter circular openings. The manholes range from 2 to 3 m in depth and from 1.4 to 2.4 m in diameter, with the larger-diameter manholes located just downstream of the crossings. Water is conveyed underneath road crossings by 46-cm-diameter ductile iron pipe laid at slopes ranging from 2 to 10%.

The upper 5 to 8 cm of the 110th Cascade cells are occupied by 4-cm-diameter washed gravel (Figure 1). Below the gravel is a minimum 20-cm-deep layer of soil mix containing 30% organic compost and 70% gravelly sand (by volume). These amended soils are underlain by a layer of 6-mm-diameter, bank-run gravel. The steep side walls of the cells are constructed of clay-soil bricks wrapped in a UV-resistant fabric. The bottom of each cell is lined with Mirafi FW-500 filter fabric (Mirafi–TenCate Geosynthetics; Pendergrass, Georgia). Distances between the bottoms of the various cells and the inverts of the outlet structures range from 7 to 10 cm, and the bottoms of the cells themselves are pitched at slopes of 1 to 2%.

A key difference between the 110th Cascade and some others referred to as "bioretention" systems is that the 110th Cascade has no underdrains; hence, only surface flow leaving the system was sampled (outflow from the system, conveyed by an existing concrete culvert, is generated when the last cell in the system fills with water). Because of the vertical drop over the system's length and the permeable materials used, some portion of the surface overflow from the system certainly passes through the amended soils, though it is impossible to know how much. That is, once a cell fills with water, incoming water may pass over the surface of the cell bottom, interacting little with the amended soils. Furthermore, it is difficult to say whether water passes from one cell to the next exclusively via the weirs and culverts connecting the cells, or whether water also is able to pass through the amended and native soils and reemerge in a lower cell ("throughflow").

Water enters the 110th Cascade from four north–south avenues and also from NW 110th Street. Figure 2 shows a vicinity map of the NW 110th Cascade bioretention system. The black rectangles represent the locations of 12 bioretention cells, and "A" and "B" represent the inlet and outlet points, respectively. The dashed line outlines the theoretical drainage catchment boundary.

Runoff from the east is conveyed by the pre-existing storm drain system and enters via a pipe at the head (east) end of the Cascade. It was only possible to monitor runoff entering the 110th Cascade at this point, denoted "A" in Figure 2. To the west of this point, runoff enters along much of the system's length as sheet flow or semi-concentrated flow not conveyed by engineered drainage structures.

Land use in the contributing basin is residential, though it is traversed by the arterial Greenwood Avenue, which has an average daily traffic (ADT) of 26 000 cars per day (cpd). Other streets in the basin have ADTs closer to 250 to 750 cpd. The 110th Cascade system was designed based on a theoretical basin area of
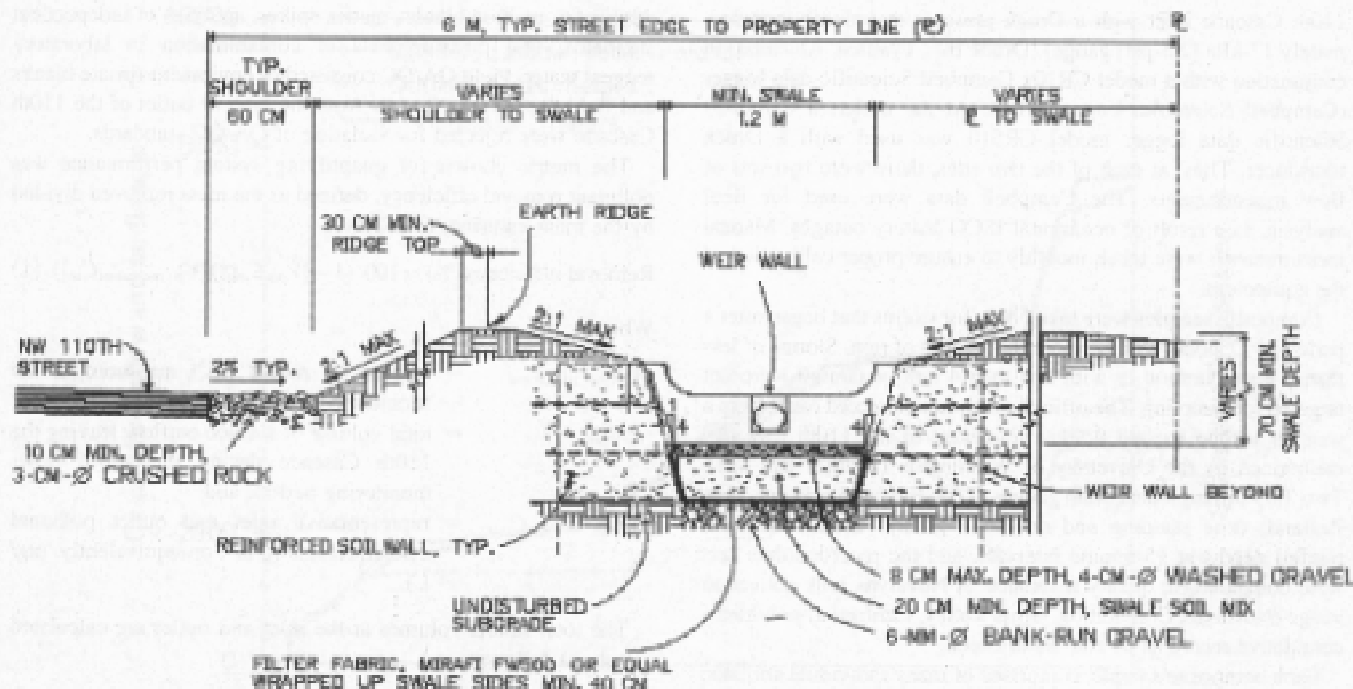
Figure 1—Typical NW 110th Cascade section looking downstream toward weir wall.

7.3 ha, with land cover in the basin 43% impervious and 57% lawns. However, it was found later that many roof downspouts in the neighborhood are tied to the sanitary sewer and not the storm drainage network. It also was discovered that some runoff was diverted out of the theoretical drainage area by excessive sediment deposition around catch basins.

These observations led to the estimate that just over 0.81 ha of impervious surface consistently drained to the 110th Cascade, with only slightly more water reaching the system in very wet conditions (i.e., infiltration capacities of local soils generally are greater than rainfall intensities).

As an additional note, the total bioretention surface area and above-ground storage volume of the 110th Cascade were

approximately 400 m^2 and 90 m^3, respectively, such that the surface-area- and storage-volume-to-watershed-area ratios (1:20 and 1:90) were similar to those found in other published field studies of bioretention performance (Davis, 2007; Dietz and Clausen, 2005; Hunt et al., 2006).

Sampling and Analysis. Flow measurements at the above-described inlet and outlet of the 110th Cascade were initiated in October 2003 and ended in March 2006; sampling was conducted from December 2004 to March 2006. Flow-paced composite samples were collected with ISCO 6700 portable water samplers (Teledyne ISCO, Lincoln, Nebraska), which measured flowrates at 5-minute time steps with ISCO 720 submerged probes. Flowrates also were measured at 15-minute time steps at the
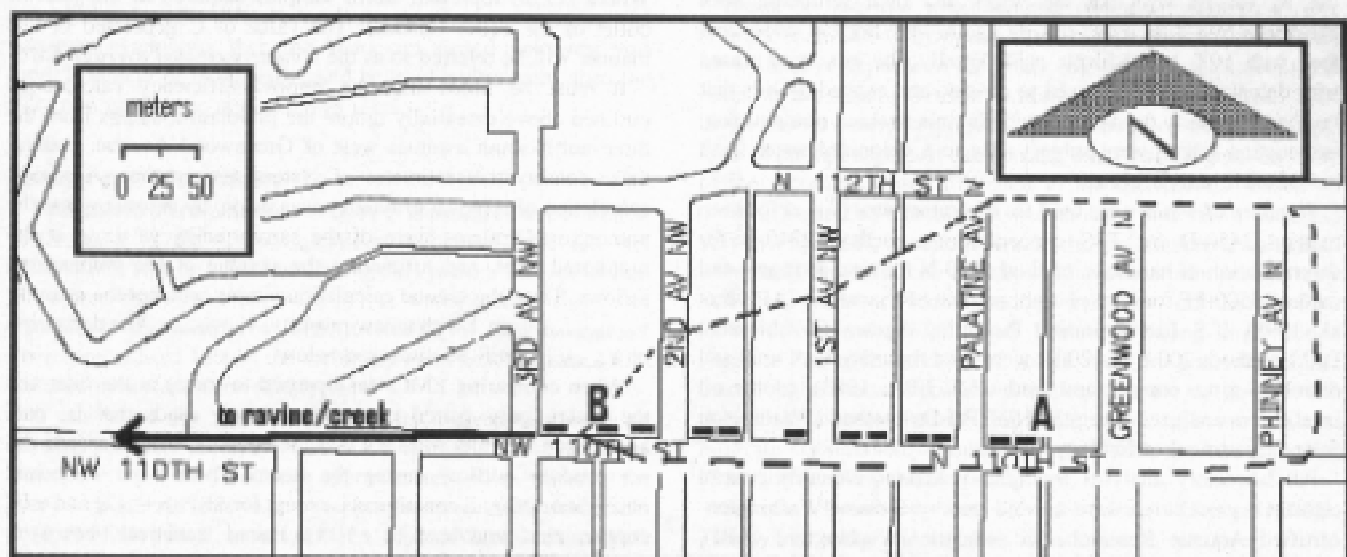

Figure 2—Vicinity map of the NW 110th Cascade bioretention system, with details discussed within text.

110th Cascade inlet with a Druck pressure transducer (approximately 17-kPa [2.5-psi] gauge) (Druck Inc., Chelsea, Alabama) in conjunction with a model CR10x Campbell Scientific data logger (Campbell Scientific, Logan, Utah). At the outlet, a Campbell Scientific data logger model CR510 was used with a Druck transducer. Thus, at each of the two sites, there were two sets of flow measurements. The Campbell data were used for final analysis, as a result of occasional ISCO battery outages. Manual measurements were taken monthly to ensure proper calibration of the equipment.

Composite samples were taken only for storms that began after a period of 12 hours with no more than 1 mm of rain. Storms of less than 1-hour duration or with less than 4 mm of rainfall were not targeted for sampling. The official precipitation record came from a weather station located 0.5 km southwest of the 110th Cascade, maintained by the University of Washington (Seattle) and SPU. Two TB3 tipping-bucket rain gauges (TB3–Envco, Auckland, New Zealand) (one standing and one in a ground trench) recorded rainfall depths at 15-minute intervals, and the recorded data sets were compared for quality assurance. A Novalynx bulk collection gauge (Novalynx Corporation, Grass Valley, California) provided a cumulative record as an additional check.

Each composite sample, comprised of many individual aliquots, allowed for determination of the event mean concentration (EMC) of a given pollutant. Ideally, composite samples represented the entire hydrograph of a given runoff event. However, in practice, pollutant concentrations (and system performance) during an event were considered to be adequately characterized if at least 10 aliquots were collected at each site and if the period of automated sampling accounted for at least 75% of the storm hydrograph (in terms of runoff volume). However, these were not stringent rules; if slightly less than 10 aliquots were collected, or if less than 75% of the storm was sampled, the collected water was analyzed regardless (as long as the inlet and outlet samples represented similar portions of the storm). Still, these criteria were met for almost all of the sampled storms.

Composite samples were submitted for laboratory analysis within 30 hours of the acquisition of the first aliquot. Samples were collected in glass jars, which were decontaminated after each use by rinsing with hot tap water and then scrubbing with phosphate-free dish soap, rinsing again with hot tap water and then with 10% hydrochloric acid. Finally, the jars were rinsed with deionized water, allowed to air-dry, and capped by lids that had been similarly decontaminated. Sample strainer, pump tubing, and suction tubing were subject only to a deionized-water flush before each sample event.

Standard Methods were used for laboratory analysis, as follows: method 2450-D for TSS concentrations; method 2340-B for determination of hardness; method 4500-N for total nitrogen, and method 4500-PF for total phosphorus and SRP analysis (APHA et al., 1998). U.S. Environmental Protection Agency (Washington, D.C.) methods 200.8 and 200.9 were used for analysis of total and dissolved zinc, copper, and lead (U.S. EPA, 1983). Motor oil levels were analyzed using the NWTPH-Dx method (Washington State Department of Ecology, 1997).

All laboratory analyses and quality assurance/quality control (QA/QC) procedures were carried out by State-of-Washington-certified Aquatic Research, Inc. (Seattle, Washington) (ARI), while field QA/QC procedures were performed by the lead author in conjunction with ARI. Laboratory QA/QC included laboratory duplicates, method blanks, matrix spikes, analyses of independent standards, and measurements of contamination in laboratory reagent water. Field QA/QC consisted of equipment rinsate blanks and field duplicates. No data from the inlet or outlet of the 110th Cascade were rejected for violation of QA/QC standards.

The metric chosen for quantifying system performance was pollutant removal efficiency, defined as the mass removed divided by the mass entering, as follows:

$$\text{Removal efficiency}(\%) = 100 \cdot (1 - [V_{out}C_{out}]/[V_{in, \text{ measured}}C_{in}]) \quad (1)$$

Where

$V_{in, \text{ measured}}$	=	volume of runoff (m^3) measured at the monitored inlet for the entire study period;
V_{out}	=	total volume of surface outflow leaving the 110th Cascade during the entire flow-monitoring period; and
C_{in} and C_{out}	=	representative inlet and outlet pollutant concentrations (g/m^3, or, equivalently, mg/L).

The total runoff volumes at the inlet and outlet are calculated simply as follows:

$$\text{Total runoff volume, } V = \Sigma \, q \, \Delta \tau \quad (2)$$

Where

q	=	instantaneous volumetric flowrate measured with the automated equipment (cm); and
$\Delta \tau$	=	time step of measurement; the calculation is summed for the entire monitoring period.

The inlet and outlet concentrations used in eq 1 were calculated by weighting the EMCs according to the runoff volumes represented by the corresponding composite samples. Therefore, the representative quantities C_{in} and C_{out} were calculated as follows:

$$C = \sum (C_1 V_1 + C_2 V_2 + \ldots + C_n V_n) / \sum (V_1 + V_2 + \ldots + V_n) \quad (3)$$

Where $(1 \ldots n)$ represent storm samples acquired at the inlet or outlet of the 110th Cascade. The value of C generated in this manner will be referred to as the *volume-weighted average EMC*.

It must be noted that the removal-efficiency calculations outlined above essentially ignore the pollutant loadings from the three north–south avenues west of Greenwood Avenue, making these conservative estimates of system performance. A second calculation of removal efficiency was made, by assuming that the unmonitored inflows were of the same quality as those at the monitored inlet, and estimating the volume of the unmeasured inflows. Thus, the second calculation simply replaces the quantity $V_{in, \text{ measured}}$ in eq 1 with a new quantity, $V_{in, \text{ inferred}}$. The derivation of $V_{in, \text{ inferred}}$ will be discussed below.

When comparing EMCs (as opposed to mass) at the inlet and the outlet, only paired observations were used; that is, data acquired at the inlet were not considered if the 110th Cascade did not produce outflow during the storm. There were 14 paired observations for all constituents, except for SRP ($n = 13$) and total copper, zinc, and lead ($n = 11$). Paired statistical tests were carried out on the data sets formed by the differences between the paired observations, that is, on the following set of values:
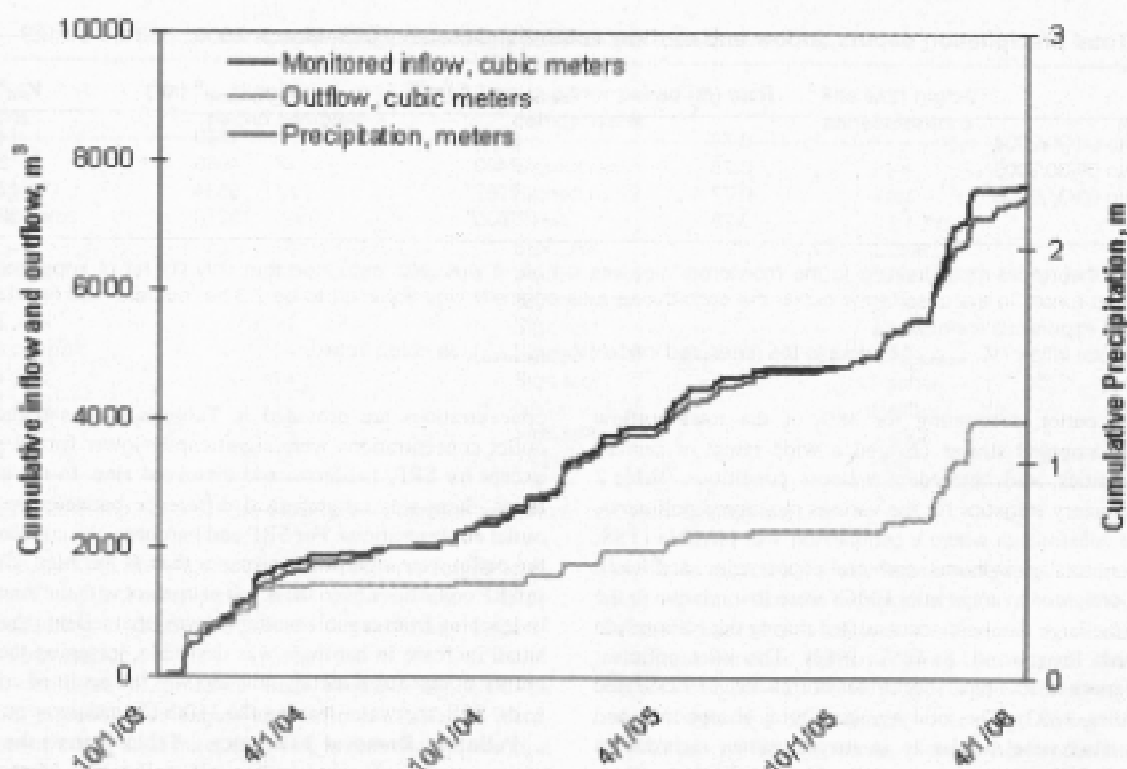
Figure 3—Cumulative precipitation depth and volumes of runoff entering and leaving the 110th Cascade, October 2003–March 2006.

$$\{\Delta_1, \Delta_2, \ldots, \Delta_n\} =$$

$$\{(C_{in,1} - C_{out,1}), (C_{in,2} - C_{out,2}), \ldots, (C_{in,n} - C_{out,n})\} \qquad (4)$$

Where

$C_{in, i}$ and $C_{out, i}$ = EMCs for the ith storm (mg/L).

If the central tendency of the Δ values was significantly different from zero, then the concentrations at the two sites were different. If the Δ values were normally distributed, and the relationship between the groups appeared to be additive, then the parametric t-test was used on the differences. If the Δ values were not normal but were symmetric, then the Wilcoxon signed-ranks test was used. If neither of these tests could be used legitimately, then the fully non-parametric sign-test was used.

Results and Discussion

Infiltration Performance. Figure 3 illustrates the infiltration performance of the 110th Cascade system over three full wet seasons and two dry seasons. During this period, 2.23 m of rain fell at the study location, 7635 m³ of water entered the 110th Cascade at the monitored inlet, and 3982 m³ left the system. Therefore, at least 48% of the incoming water never left the 110th Cascade as surface flow (Table 1).

It was found that the rainfall depth for a given storm was an accurate predictor (coefficient of determination $R^2 = 0.95$) of the water entering at the inlet, with approximately 40 m³ entering for every 1 cm of rain (this value accounts for many small storms that produced little runoff, as a result of a depression and interception storage in the basin). This relationship changed only slightly, as a result of antecedent wetness, and corresponded to the area of

impervious surface determined (by field reconnaissance during storms) to drain to the monitored 110th Cascade inlet—just over 0.4 ha. It also was estimated, from field observations during storms, that a nearly equivalent area of impervious surface drained to the 110th Cascade between the monitored inlet and outlet. Therefore, the total area estimated to drain to the system was approximately 0.81 ha, and the total runoff volume entering likely was double that measured at the monitored inlet. Given this, it would be more accurate to say that closer to 74% of the water entering the 110th Cascade was retained (rather than 48%).

Based on previous measurements of local evaporation rates (Horner et al., 2004), it appears that evaporation can account only for a small percentage of the water lost between the inlet(s) and outlet. In the months October to March, when approximately 85% of the annual precipitation falls, pan evaporation depths are only 10% of rainfall depths. It can be said, then, that the great majority of the incoming water infiltrated to the native soils. Based on preconstruction soil borings, it was thought that native soils had very low hydraulic conductivities, so that pollutant removal would be mostly the result of filtration by the bioretention system's amended soils or sedimentation, and not infiltration loss. However, the volume of runoff infiltrated during large storms suggests that conductivities of native soils are generally higher than thought. It also is possible that local soils are not uniform and that small pockets of more permeable native soils were able to infiltrate considerable amounts of water. Still, the true dynamics of subsurface flow remain ambiguous.

Sample Numbers and Event Mean Concentrations. Twenty-six composite samples were taken at the inlet; the 26 sampled storms represented 42% of the total inflow volume at this location during the sampling period. Fourteen composites were

Table 1—Total precipitation depths, inflow and outflow volumes, October 2003–March 2006.

Period	Rain (m)	$V_{in, measured}$[a] (m³)	$V_{in, inferred}$[b] (m³)	V_{out}[a] (m³)
10/10/2003 to 09/30/2004	0.73	2375	4750	1446
10/01/2004 to 09/30/2005	0.73	2493	4986	821
10/01/2005 to 03/31/2006	0.77	2767	5534	1715
Total	2.23	7635	15270	3982

[a] While the theoretical area draining to the monitored inlet was 4.1 ha, it was later estimated that only 0.4 ha of impervious surface contributed runoff. In the case of the outlet, the contributing area originally was assumed to be 7.3 ha, but later estimated to be only 0.61 ha of impervious surface.

[b] Inferred total inflow ($V_{in, inferred}$) is double the measured inflow ($V_{in, measured}$) as noted in text.

taken at the outlet, accounting for 38% of the total outflow volume. The sampled storms covered a wide range of rainfall depths, intensities, and antecedent wetness conditions. Table 2 gives the summary statistics for the various monitored pollutants.

For those constituents where a comparison was possible (TSS; total nitrogen; total phosphorus; and total copper, zinc, and lead), the volume-weighted average inlet EMCs were low relative to the medians of the large database accumulated during the Nationwide Urban Runoff Program (U.S. EPA, 1983). The inlet pollutant levels were more or less typical of urban stormwater in the Seattle area (Chandler, 1993). The total nitrogen, total phosphorus, and TSS levels also were similar to in-stream values recorded in Piper's Creek during storm events (King County, 2006).

Incidentally, the volume-weighted average EMCs were quite similar to the arithmetic means of the EMCs for almost all pollutants at the two sites, and the calculated removal efficiencies changed only slightly when the means were used in eq 1. The similarity exists because, for the largest storms, the EMCs were not particularly high or low. The only cases for which the volume-weighted average EMC did not fall within the 90% confidence interval on the statistical mean was for dissolved copper at the inlet, dissolved zinc at the outlet, and hardness at both sites. In each case, a low EMC for a moderately large storm affected the volume-weighted value, but had much less effect on the arithmetic mean.

Paired Comparisons, Inlet Versus Outlet. The results of the paired statistical comparisons between the inlet and outlet

concentrations are provided in Table 3. It was found that the outlet concentrations were significantly lower for all pollutants, except for SRP, hardness, and dissolved zinc. In the case of the latter, there was no statistical difference between the inlet and outlet concentrations. For SRP and hardness, the concentrations at the outlet were significantly greater than at the inlet. The increase in SRP could have been the result of contact with the amended soils or leaching from organic matter (leaves) that fell into the cells. The small increase in hardness was desirable, lessening the bioavailability of dissolved metals; this too was the result of contact with soils. Still, the water leaving the 110th Cascade was quite soft.

Pollutant Removal Efficiency. Table 4 gives the estimated mass-removal efficiencies for all pollutants. Method 1 was described in the Site Description and Methods section, and gives conservative values. Method 2 assumes that the true total inflow to the system ($V_{in, inferred}$) was double the measured quantity ($V_{in, measured}$; see also Table 1) and that pollutant concentrations at all inlets were equivalent.

The 110th Cascade exhibits high removal efficiencies for copper, zinc, and lead, similar to other studies of bioretention systems where these metals have been monitored. With regard to TSS removal, the 110th Cascade performed as well or better than other bioretention systems studied in real-weather conditions. Bioretention studies thus far have had different results in terms of TSS removal; for instance, the system in North Carolina (Hunt et al., 2006) was found to export TSS, rather than remove it. The North Carolina system was monitored immediately following

Table 2—Volume-weighted-average EMCs[a] at inlet and outlet of the 110th Cascade.

Constituent	Units	Inlet	Outlet	NURP[b]
TSS	mg/L	120	30	183
Total nitrogen	mg/L	1.15	0.81	1.9
Total phosphorus	µg/L	210	133	420
SRP	µg/L	13	36	
Total copper	µg/L	16	6.3	40
Total zinc	µg/L	120	47	210
Total lead	µg/L	17	4.6	179
Dissolved copper	µg/L	3.6	2.9	–
Dissolved zinc	µg/L	49	26	–
Dissolved lead	µg/L	<1	<1	–
Hardness	mg/L	8.3	10	–
TPH (motor oil)[c]	mg/L	1.4	0.22	

[a] EMCs determined from analysis of composite samples.

[b] Nationwide Urban Runoff Project (U.S. EPA, 1983). All values are medians.

[c] Motor oil levels were analyzed with the NWTPH-Dx method (Washington State Department of Ecology, 1997).

Table 3—Paired statistical comparisons between inlet and outlet concentrations.

Constituent	Number of paired samples	Test used for paired comparisons	Site with higher concentrations	p-value
TSS	14	Signed ranks	Inlet	0.001
Total nitrogen	14	Signed ranks	Inlet	0.014
Total phosphorus	14	T-test	Inlet	0.012
SRP	13	Sign test	Outlet	0.000
Total copper	11	Signed ranks	Inlet	0.002
Total zinc	11	Signed ranks	Inlet	0.006
Total lead	11	Sign test	Inlet	0.001
Dissolved copper	14	Signed ranks	Inlet	0.05
Dissolved zinc	14	Sign test	Neither	0.37
Dissolved lead	14	NA*	Neither	NA*
Hardness	14	Sign test	Outlet	0.002
Motor oil	14	T-test	Inlet	0.000

* Not applicable: too many results were below detection to perform statistical calculations.

construction, and the investigators posited that there might be an initial "wash" of loose sediments from these systems. Water-quality monitoring at the 110th Cascade for this study began 1 year after construction.

Clearly, estimates of pollutant mass removal depended on assumptions regarding the unmeasured inflows (Table 4). Whatever treatment might have been occurring within the bioretention system, the sheer volume of water infiltrated or otherwise detained during the study period had an enormous effect on the removal-efficiency calculations. This is most apparent when considering the case of phosphorus. As mentioned, SRP concentrations at the outlet were significantly higher than at the inlet; however, as a result of runoff retention (and efficient removal of particulate phosphorus), total phosphorus was removed at a rate of at least 67%, despite the SRP increase.

With regard to other pollutants, total nitrogen was removed at approximately the same rate as total phosphorus. Motor oil was the pollutant eliminated most effectively, with removal efficiencies ranging from 92 to 96%, depending on the method used for estimation.

On shorter time scales, mass pollutant removal from storm to storm also was dependent on the amount of water retained by the

Table 4—Pollutant removal efficiencies (%).*

Constituent	Method A	Method B
TSS	87	93
Total nitrogen	63	82
Total phosphorus	67	83
SRP	-44	26
Total copper	80	90
Total zinc	80	90
Total lead	86	93
Dissolved copper	58	79
Dissolved zinc	72	86
Dissolved lead	Not applicable	Not applicable
Hardness	37	69
TPH (motor oil)	92	96

* Method A does not account for any inflows besides those measured at the monitored inlet; method B assumes that the true inflow volume was double that measured at the monitored inlet.

system. In most storms, all water entering the 110th Cascade was retained, such that the removal efficiency was 100%. A set of threshold curves was created to illustrate the tendency of the system to produce outflow, given storm size and antecedent wetness (Figure 4). These curves were created by examining rainfall data for 235 storms occurring during the 2.5-year monitoring period. In storms plotting below the dark line, the 110th Cascade did not overflow (i.e., did not send water to the conventional drainage system and to Piper's Creek). In storms plotting above the pale line, the system always produced surface outflow. In storms plotting between the two lines, the volume of outflow (relative to inflow) depended on rainfall-intensity patterns. As mass removal depends on volume control, system performance will vary according to hydrologic patterns.

Pollutant Concentration Reduction. The percent decrease in pollutant concentration from inlet to outlet was analyzed for each sampled storm. Percent decreases in concentrations generally were well-correlated with reduction of the TSS concentration. Only in the case of SRP was the correlation with TSS decrease statistically insignificant ($p = 0.12$). The p-values for correlation with TSS were <0.05 for all other constituents (Table 5).

The TSS was not the only constituent that showed strong correlations with other pollutants, in terms of percent decrease. For instance, changes in concentrations of total copper and total phosphorus correlated well with the decreases of other pollutants, when analyzed on a storm-to-storm basis (Table 5). However, this was explained by covariance with TSS. Once the influence of TSS was eliminated statistically, total copper and total phosphorus explained little of the variability in the other data.

While the TSS concentration reduction was correlated with reduction of dissolved copper and dissolved zinc levels, the connection was strongest with constituents associated with particles, such as particulate zinc (Pearson's $r = 0.75$) and particulate phosphorus ($r = 0.85$). Interestingly, the correlation between reduction of TSS and total zinc levels was stronger than that between TSS and particulate zinc, even though the correlation between concentration decreases of TSS and dissolved zinc was weaker. This trend appears to be only coincidental.

The correlation of TSS removal with removal of other pollutants helps explain the dominant mechanism of treatment by the 110th Cascade bioretention system and possibly other such systems. Complete retention of incoming street runoff effectively
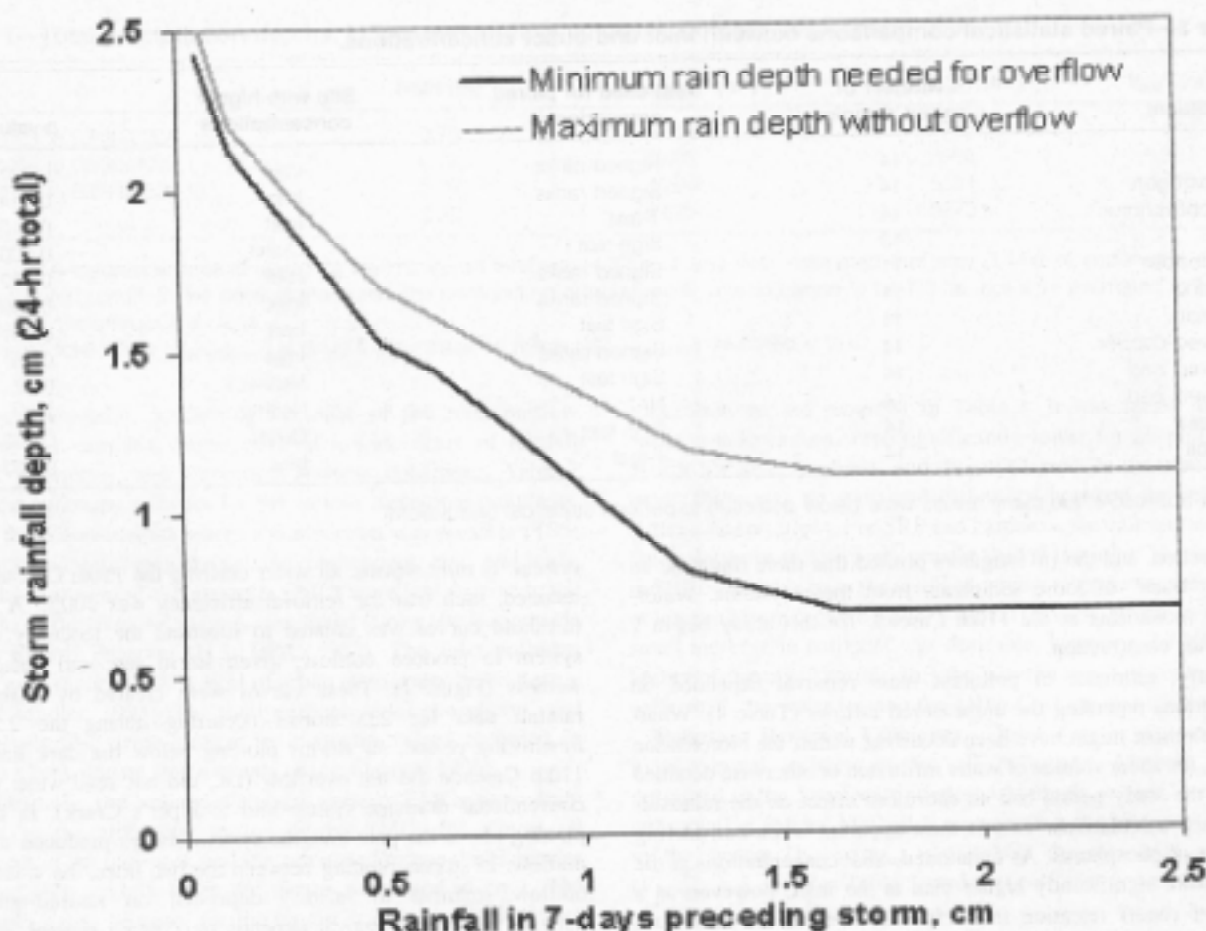
Figure 4—Tendency of the 110th Cascade to overflow as a function of event rainfall depth and antecedent wetness.

means capture of sediments. Because pollutants generally are associated with sediments, all pollutants are captured in this way. As such, volume control could be the most important feature of this system. With regard to water that still manages

to leave the system, high detention times allow for sedimentation. Another potential treatment mechanism is that water is filtered while passing through the amended soils before leaving the system.

Table 5—Correlations of storm-to-storm percent pollutant concentration reduction.*

	TSS	Total nitrogen	Total phosphorus	SRP	Particulate phosphorus	Total zinc	Dissolved zinc	Particulate zinc	Total copper	Dissolved copper	Particulate copper	Total lead	Motor oil
TSS	1	0.59	0.66	0.46	0.85	0.51	0.57	0.75	0.69	0.56	0.70	0.60	0.57
Total nitrogen	0.03	1	0.87	0.48	0.85	0.62	0.07	0.61	0.64	0.40	0.37	0.22	0.10
Total phosphorus	0.01	0	1	0.53	0.96	0.81	0.20	0.79	0.64	0.40	0.12	0.06	0.11
SRP	0.12	0.09	0.06	1	0.36	0.71	0.44	0.54	0.13	0.20	0.12	0.06	0.11
Particulate phosphorus	0	0	0	0.22	1	0.57	0.30	0.82	0.83	0.48	0.64	0.63	0.44
Total zinc	0	0.04	0	0.02	0	1	0.68	0.94	0.53	0.22	0.40	0.24	0.16
Dissolved zinc	0.03	0.81	0.50	0.13	0.31	0.02	1	0.46	0.39	0.48	0.44	0.54	0.51
Particulate zinc	0.01	0.05	0	0.04	0	0	0.15	1	0.42	0.13	0.30	0.10	0.02
Total copper	0.02	0.01	0.03	0.73	0	0.09	0.24	0.19	1	0.76	0.86	0.75	0.67
Dissolved copper	0.04	0.14	0.16	0.51	0.10	0.52	0.06	0.71	0.01	1	0.8	0.78	0.57
Particulate copper	0.02	0.22	0.26	0.75	0.05	0.23	0.18	0.37	0	0	1	0.82	0.78
Total lead	0.05	0.40	0.52	0.87	0.11	0.48	0.09	0.77	0	0	0	1	0.87
Motor oil	0.04	0.47	0.75	0.74	0.15	0.67	0.08	0.96	0.04	0.04	0.01	0	1

* Numbers above the diagonal are Pearson's correlation coefficients; numbers below the diagonal are p-values. P-values <0.005 are set to 0.

Table 6—Outlet pollutant concentrations measured in field-based biofiltration studies.[a]

Constituent	Unit	Dietz and Clausen (2005)	Hunt et al. (2006)	Davis (2007)	This Study
TSS	mg/L	NA	99	17	30
Total nitrogen	mg/L	0.8 to 1.0	5.2	NA	0.81
Total phosphorus	µg/L	60	3000	180	133
SRP	µg/L	NA	2300	NA	36
Total copper	µg/L	<5	50	4	6.3
Total zinc	µg/L	<10	20	53	47
Total lead	µg/L	<5	9	4	4.5

[a] NA = not available.

Effluent Quality. In some cases, percent-reductions of pollutant concentration can be misleading indicators of treatment system performance. For some systems, outlet pollutant concentrations vary little, regardless of the inlet concentration (Barrett, 2005). It may be the case that bioretention systems are able to put out somewhat consistent, "reliable" effluent pollutant levels, but that percent reduction in concentration (and mass) will depend on local runoff quality (and system size relative to its contributing basin).

In general, there did not appear to be strong functional relationships between pollutant levels at the 110th Cascade's inlet and outlet. For instance, while TSS varied greatly at the inlet, seemingly linked to hydrologic variables, TSS levels at the outlet varied relatively little, and there was no significant correlation between the inlet and outlet TSS levels. Similarly, total lead concentrations varied greatly at the inlet and were highly correlated with TSS. Total lead and TSS also were correlated at the outlet, but the total lead levels at the two sites were not correlated. Only for total nitrogen, total phosphorus, and dissolved copper did it appear that there was some significant correlation between the levels at the inlet and outlet.

With this in mind, it is worthwhile to characterize outlet concentrations from the 110th Cascade and compare them with those from other bioretention studies. Table 6 compares effluent pollutant levels with the few other bioretention field studies that have been published in the literature. Unfortunately, not all authors have reported whether there are correlations between pollutant levels at their monitored inlets and outlets, or whether outlet concentrations appear to vary independently.

If it is true that effluent quality is not a function of influent quality, it is useful to know the pollutant levels that can be expected at the outlet of a bioretention facility. Table 7 presents the reliable maximum and irreducible minimum effluent pollutant concentrations observed at the 110th Cascade. The reliable maximum is here defined as the EMC that was exceeded in only 10% of the runoff events, while the irreducible minimum is the EMC that was exceeded 90% of the time. These values were calculated as two-sided prediction intervals with $\alpha = 0.10$, using both parametric (t-distribution) and non-parametric (ranks) methods (Helsel and Hirsch, 1991). Data were log-transformed before calculating the parametric prediction intervals, except where noted in Table 7.

Also included in Table 7 are non-parametric effluent values derived from the field investigation in Maryland (Davis, 2007), which is the only published study that provided EMCs for all sampled storms. The values from the Maryland study are similar to those found in the present investigation for TSS, total zinc, and total copper. Outlet total phosphorus and total lead concentrations varied less at the 110th Cascade than at the Maryland facility.

Table 7—Irreducible minimum and reliable maximum pollutant concentrations in outflow from NW 110th cascade.

Constituent	Unit	Non-parametric[a]		Parametric[a]	
		Irreducible minimum	Reliable maximum	Irreducible minimum	Reliable maximum
TSS[b]	mg/L	9 (4)	40 (39)	7	48
Total nitrogen	mg/L	0.59	1.27	0.50	1.55
Total phosphorus	µg/L	81 (30)	210 (1320)	75	256
SRP	µg/L	22	86	18	102
Total copper	µg/L	3.9 (3.0)	7.6 (10)	3.2	9.3
Total zinc	µg/L	39 (<30)	106 (120)	26	119
Total lead	µg/L	1.6 (<2)	6.8 (46)	1.4	10
Dissolved copper	µg/L	1.8	4.7	1.2	7
Dissolved zinc	µg/L	14	54	13	72
Dissolved lead	µg/L	<1	<1	<1	<1
Hardness	mg/L	7	17	6	23
Motor oil	mg/L	<0.15	0.32	NA[c]	NA[c]

[a] Non-parametric (ranks) and parametric (t-distribution) methods (Helsel and Hirsch, 1991). Numbers in parentheses are corresponding values from Davis (2007), given where available.

[b] TSS data were not transformed in computing the parametric values.

[c] Not applicable; too many results were below detection to perform parametric calculations.

As shown, the irreducible minimum dissolved copper and dissolved zinc concentrations in effluent from the 110th Cascade were 1.2 to 1.5 µg/L and 13 to 14 µg/L, respectively. These values are only slightly less than the State of Washington's chronic toxicity criteria (1.8 and 19 µg/L, respectively) for a hardness of 12 mg/L as calcium carbonate (the average hardness of all outlet samples acquired) (Washington State Administrative Code, 1992). That is, in the majority of storms, the effluent concentrations exceed the State's standards. It must be noted that toxicity criteria are applied in the receiving water body downstream from the discharge, where there is a dilution effect. However, during storms, the great majority of water in an urban stream might be urban runoff, as opposed to base flow. Therefore, it is possible that treatment of runoff by bioretention might not sufficiently decrease dissolved metals levels for aquatic biota. The consolation is that infiltration of runoff into native soils (at least at the 110th Cascade) greatly diminishes the frequency and duration of stormwater discharges to the receiving creek.

Summary and Conclusions

Bioretention is an alternative to conventional stormwater treatment methods. Bioretention systems are more versatile than conventional systems and are integrated into a neighborhood or streetscape. The SPU has embraced the techniques of LID, including bioretention, in its desire to return local creeks to more natural conditions. In 2002, SPU constructed the 110th Cascade bioretention system in the right-of-way of an existing street, as part of a larger program to monitor and assess the viability of these systems.

For two wet seasons and one dry season, the quality and quantity of runoff were measured at the inlet and outlet of the 110th Cascade. For this time period, at least 48% of the incoming runoff either infiltrated to native soils or was lost to evapotranspiration. Given an approximation of the volume of the unmeasured inflows, it was estimated that closer to 74% of all inflows were retained.

Pollutant concentrations at the outlet were significantly lower ($p<0.05$) than at the inlet for all constituents, except dissolved zinc and soluble reactive phosphorus. The SRP levels were significantly greater at the outlet ($p<0.001$). Based on the estimate that 48% of the inflows were retained, the system removed roughly 87% of the total influent mass of TSS, 63% of total nitrogen, 67% of total phosphorus, 80% of total copper and total zinc, 86% of total lead, and 92% of motor oil. These values suggest effective pollutant removal, yet are conservative estimates of system performance, because they take into account only pollutants that entered at the monitored inlet. If indeed 74% of the runoff was retained, then 93% of TSS was removed, as was 82% of total nitrogen and 83% of total phosphorus, 90% of total copper and total zinc, 93% of total lead, and 96% of motor oil.

Outlet concentrations were similar to those found in previous field monitoring of a bioretention facility in Maryland (Davis, 2007) and, in the case of total nitrogen, similar to those found at a facility in Connecticut (Dietz and Clausen, 2005). However, there are still too few data available to identify the precise factors governing outlet concentrations from bioretention facilities.

The results from the 110th Cascade suggest that bioretention systems are capable of achieving a high level of treatment in real-weather conditions. In this case, the system was small enough to fit into an existing street right-of-way. However, appropriate system sizing likely will depend on local soil infiltration rates, rainfall patterns, and basin size. More research is needed to determine which variables, including system size, influence system performance and whether performance is best characterized by mass removal efficiency calculations or some reliable effluent quality that is independent of influent quality.

References

American Public Health Association; American Water Works Association; Water Environment Federation (1998) *Standards Methods for the Examination of Water and Wastewater*, 20th ed.; American Public Health Association: Washington, D.C.

Barrett, M. E. (2005) Performance Comparison of Structural Stormwater Best Management Practices. *Water Environ. Res.*, **77**, 78–86.

Booth, D. B.; Jackson, C. R. (1997). Urbanization of Aquatic Systems: Degradation Thresholds, Stormwater Detection, and the Limits of Mitigation. *J. Am. Water Resour. Assoc.*, **33**, 1077–1089.

Chandler, R. D. (1993) Modeling and Nonpoint Source Pollution Loading Estimates in Surface Water Management. Unpublished Master's thesis, University of Washington Department of Civil Engineering, Seattle.

Davis, A. P. (2007) Field Performance of Bioretention: Water Quality. *Environ. Eng. Sci.*, **24**, 1048–1064.

Davis, A. P.; Shokouhian, M.; Sharma, H.; Minami, C. (2001) Laboratory Study of Biological Retention for Urban Stormwater Management. *Water Environ. Res.*, **73**, 5–14.

Davis, A. P.; Shokouhian, M.; Sharma, H.; Minami, C.; Winogradoff, D. (2003) Water Quality Improvement Through Bioretention: Lead, Copper and Zinc Removal. *Water Environ. Res.*, **75**, 73–82.

Dietz, M. E.; Clausen, J. C. (2005) A Field Evaluation of Rain Garden Flow and Pollutant Treatment. *Water Air Soil Pollut.*, **167**, 123–138.

Helsel, D. R.; Hirsch, R. M. (1991) *Statistical Methods in Water Resources: Techniques of Water-Resources Investigations, Chapter A3 of Book 4*; U.S. Geological Survey: Reston, Virginia.

Horner, R. R.; Lim, H. K.; Burges, S. J. (2004) Hydrologic Monitoring of the Seattle Ultra-Urban Stormwater Management Projects—Summary of the 2000–2003 Water Years. Water Resources Series Technical Report 181, University of Washington, Department of Civil Engineering, Seattle.

Hsieh, C. H.; Davis, A. P. (2005) Multiple-Event Study of Bioretention for Treatment of Urban Storm Water Runoff. *Water Sci. Technol.*, **51**, 177–181.

Hunt, W. F.; Jarrett, A. R.; Smith, J. T.; Sharkey, L. J. (2006) Evaluating Bioretention Hydrology and Nutrient Removal at Three Field Sites in North Carolina. *J. Irrig. Drainage Eng.*, **132**, 600–608.

King County (2006) Published and unpublished water quality data for Piper's Creek from King County (WA) Department of Natural Resources' Water Quality Monitoring Program, King County, Washington.

Konrad, C. P.; Booth, D. B.; Burges, S. B. (2005) Effects of Urban Development in the Puget Lowland, Washington, on Interannual Streamflow Patterns: Consequences for Channel Form and Streambed Disturbance. *Water Resour. Res.*, **41**, 1–15.

Marsalek, J.; Rochfort, Q.; Brownlee, B.; Mayer, T.; Servos, M. (1999) An Exploratory Study of Urban Runoff Toxicity. *Water Sci. Technol.*, **39**, 33–39.

Muthanna, T. M.; Viklander, M.; Gjesdahl, N.; Thorolfsson, S. T. (2007) Heavy Metal Removal in Cold Climate Bioretention. *Water Air Soil Pollut.*, **183**, 391–402.

Sun, X.; Davis, A. P. (2007) Heavy Metal Fates in Laboratory Bioretention Systems. *Chemosphere*, **66**, 1601–1609.

U.S. Environmental Protection Agency (1983) Final Report of the Nationwide Urban Runoff Program (NURP). Publication PB84-185545. U.S. Environmental Protection Agency: Washington, D.C.

Washington State Administrative Code (1992) Washington State Administrative Code Chapter 173-201A-240: Water Quality Standards for the Surface Waters of the State of Washington.

Washington State Department of Ecology (1997) *Analytical Methods for Petroleum Hydrocarbons*, Publication ECY 97-602. Washington State Department of Ecology: Olympia, Washington.