TESTING OF ULTRA-URBAN STORMWATER BEST MANAGEMENT PRACTICES

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(The opinions, findings, and conclusions expressed in this report are those of the authors and not necessarily those of the sponsoring agencies.)

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ACRONYMS, ABBREVIATIONS, AND SYMBOLS

BMP	Best Management Practice
COD	Chemical Oxygen Demand
EMC	Event Mean Concentration
EPA	Environmental Protection Agency
FHWA	Federal Highway Administration
MDL	Method Detection Limit
PRE	Period Removal Efficiency
SD	Standard Deviation
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
UVA	University of Virginia
VDOT	Virginia Department of Transportation
VTRC	Virginia Transportation Research Council

ABSTRACT

Ultra-urban areas where conventional best management practices (BMPs) are neither feasible nor cost-effective present a challenge to stormwater management. Although new BMPs have been developed for such space-limited environments, the field performance of these technologies is still largely undocumented.

This study monitored the field performance of four ultra-urban BMPs: three oil and grit separators (Isoilater, Stormceptor™, and Vortechs Stormwater Treatment System™) and a bioretention area. Storm sampling data for each site were analyzed to calculate the removal efficiency for each constituent monitored. Because the Vortechs system was installed improperly, its removal efficiency results in this study are not reliable. Therefore, the system could not be fully evaluated.

The results of the study are site specific. The performance of the BMPs was affected by varying factors. The study, thus, concludes that the data and study site conditions must be evaluated carefully before results can be extrapolated to compare the relative and potential performance of a particular BMP under different site conditions.

FINAL REPORT

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INTRODUCTION AND BACKGROUND

The Virginia Department of Transportation (VDOT), in accordance with the requirements of various federal and state regulations, routinely provides stormwater runoff control facilities (best management practices, or BMPs) at highway construction sites. BMPs are designed to minimize the potential impact of pollutants in highway runoff on the quality of the receiving water. These systems are implemented to maintain the quality of receiving waters crossed by highways and to satisfy the permit requirements of the National Pollutant Discharge Elimination System. Environmental regulatory agencies such as the U.S. Environmental Protection Agency (EPA) have focused attention on nonpoint source pollution such as urban and highway runoff. Both structural and nonstructural BMPs are used as pollution prevention and mitigation practices. Many innovations were recently developed for structural BMPs, particularly for areas with limited land space, and they are being used throughout the United States as pollution prevention devices for controlling highway runoff.

The "ultra-urban" environment (a term coined by the city of Alexandria, Virginia) has been used to describe metropolitan areas where space for stormwater BMP implementation is limited. These environments are characterized by a high density of paved surfaces or buildings that result in a high degree of imperviousness. Buildings, parking facilities, urban streets, highways, or walkways cover a majority of the land area, with imperviousness greater than 50% in ultra-urban areas (up to 100% in some cases) and with less than 4,047 m^2 of available land for BMP implementation (Federal Highway Administration [FHWA], 1999). Increased automobile use, land use practices, high levels of trash and debris, and even fecal matter contributed by pets are all major influences of constituents loadings in stormwater runoff in ultra-urban areas (EPA, 1999). Particular land uses and activities are known to produce higher concentrations of hydrocarbons, trace metals, and toxicants than are found in typical stormwater runoff (Maryland Department of the Environment, 1998). A greater level of stormwater treatment is needed to control pollutant washoff after construction at "hot spot" sites where higher pollutant concentrations are expected. In addition, untreated stormwater runoff from hot spots cannot be allowed to infiltrate groundwater, where it might contaminate water supplies. Water-soluble pollutants, such as chloride, nitrate, copper, dissolved solids, and particular polycyclic aromatic hydrocarbons, can migrate into the groundwater and potentially contaminate wells (Maryland Department of the Environment, 1998).

Heavily urbanized areas present special challenges for urban diffuse pollution control and are approached with innovative BMPs. A BMP is a means determined to be reasonable and cost-effective of reducing the amount of pollution generated by nonpoint sources to a level in compliance with water quality standards (Wanielista, 1993). These approaches aim to mitigate erosion and pollution from stormwater with technologies appropriate to site constraints, inflow volumes, and pollutant loads. Innovative BMPs are implemented where conventional BMPs such as detention ponds, infiltration trenches and basins, grass swales, and buffers may be inappropriate. Design guidelines for these innovative BMPs are primarily based on treating the "first flush" of runoff, which is the first 12.7 mm of runoff or water quality volume of a storm. Several less land-intensive ultra-urban BMPs can be employed to intercept stormwater runoff and prevent the transfer of pollutants downstream. Moreover, some of the conventional BMPs can be adapted to the ultra-urban environment (FHWA, 1999).

Various proprietary BMPs have been promoted as effective stormwater quality and quantity control devices suitable for the ultra-urban environment. Hydrodynamic structures such as the Stormceptor™ (Stormceptor), Vortechs Stormwater Treatment System™ (Vortechs), Downstream Defender™, and BaySaver Separation System™ are commercially available for treating stormwater runoff. Other available commercial products include filtering structures such as the StormFilter™ and the StormTreat System™. Further, bioretention technology, sand filters, and the multi-chamber treatment train offer additional pollution control alternatives for the ultra-urban environment. Most ultra-urban BMPs are still in their early implementation stages as they have not been fully tested in the field. Design removal efficiencies for these BMPs are based on tests of scaled models in the laboratory. Based on the reported removal efficiencies from manufacturers, space-limited BMPs can provide removal of total suspended solids (TSS) as high as 80%. Some space-limited BMPs also claim high nutrient, metal, oil, and grease removal. Their performance is critical and necessary in sensitive areas where they are the only management control option being implemented. There is a significant need to test and document the performance of various ultra-urban BMPs in order to improve methods for treating runoff from ultra-urban areas and make recommendations for doing so.

During the past few years, VDOT installed many ultra-urban BMPs in various construction locations. Information on their field performance is needed. Maintenance requirements for these second-generation BMPs are of great interest to VDOT and transportation departments in other states. The present study was, therefore, initiated in 1998 to provide this information.

PURPOSE AND SCOPE

The purpose of this study was to evaluate the use of ultra-urban BMPs in Virginia as innovative stormwater control technologies for application to highway nonpoint source pollution. The objectives were to characterize the system performance of four ultra-urban BMPs and determine their pollutant removal efficiencies through storm event sampling of several EPA-recommended urban runoff constituents. The sediment accumulation, maintenance requirements, design, and costs associated with each BMP were used in the overall performance evaluation.

METHODS

The research objectives were carried out by sampling the influent and effluent flows for each BMP during selected storm events. Each monitoring site was equipped with automatic sampling equipment. During storm events, samplers collected continuous flow, rainfall data, and runoff samples at specified time intervals. In general, flow-proportional composite event mean concentrations (EMCs) were used to determine pollutant removal efficiencies. If flow data were unavailable, average influent and effluent concentrations were used instead. In addition, sediment accumulation was measured regularly during the sampling periods for the three oil and grit separators and, when possible, sediment accumulation monitoring was continued after sampling had been completed. The design and actual costs of the BMPs were considered and evaluated.

Site Selection

Four locations in Virginia were selected for sampling: the Route 17 Bypass in Warrenton, the Monticello High School parking lot in Charlottesville, UVA's Scott Stadium parking lot in Charlottesville, and UVA's Facility Management parking lot in Charlottesville. Table 1 summarizes the characteristics of the sites.

Table 1. Monitoring Sites

Location	BMP Type	Runoff Type	Drainage Area (m^2)	Sampling Period	Water Quality Parameters Sampled	No. Storm Events Sampled
Route 17 Bypass, Warrenton	Isoilater	Highway	809	May-Oct 99	TSS, TP, COD, oil and grease, sediment analysis	7
Monticello High School, Charlottesville	Bioretention area	Automobile parking lot	3,157	Sept-Nov 99	TSS, TP, COD, oil and grease	10
UVA Scott Stadium, Charlottesville	Stormceptor	Automobile parking lot (under construction)	10,117	Nov 99-Apr 00	TSS, TP, COD, TN, copper, zinc, oil and grease, sediment analysis	6
UVA Facility Management, Charlottesville	Vortechs	Maintenance parking lot	2,428	Mar-Apr 00	TSS, TP, COD, TN, copper, zinc, oil and grease	7

The selection of sampling sites was based on several criteria. Of primary concern were the significant costs associated with the purchase and installation of ultra-urban BMPs. Therefore, priority was given to sites with existing ultra-urban BMPs owned by VDOT or other entities that were available for field monitoring within the project time frame. Sites consisting of representative innovative BMPs in ultra-urban land use settings and sites that were suitable for highway application through VDOT maintenance and construction programs were considered.

Sites were also chosen within reasonable proximity to the University of Virginia (UVA) that were accessible for installation of stormwater field monitoring equipment. Sites with steep slopes, deep manholes, improper headspace, and in-line obstacles that could create difficulties for monitoring during equipment installation and operation were avoided.

Preparation of Sampling Sites

Preparation of each site included the establishment of monitoring stations at appropriate inlets and outlets. Plywood boxes to house the automatic samplers were constructed and then secured in the field. Automatic samplers were calibrated and programmed for sampling and flow measurements at each station. Level and volume calibrations were performed in the UVA Stormwater Laboratory in accordance with the American Sigma 900 MAX *Automatic Samplers User's Manual* (American Sigma, 1998), and additional calibrations were made in the field when necessary. The sample intake strainer and depth sensor were positioned in the mainstream of the inlet and outlets parallel with the flow. The depth sensor was secured in the center of the pipe with a hose clamp, and the strainer was secured adjacent to it. This was the typical monitoring field setup for all sites.

Field preparation also included the construction of weirs to measure flows where necessary (i.e., channels with irregular geometry or low flow). Sampling equipment and rain gages were set up at each monitoring station when weather conditions allowed sampling equipment to be left outside. Flow was measured at inlets and outlets. Depth sensors compatible with the automatic samplers were the primary devices used to measure flow. Manning's equation was applied to translate depth to flow for channels of regular geometry. When weirs were constructed, the weir equation was applied to determine flow for irregular channels.

Description of Test Sites

Isoilater Test Site

The Isoilater site is adjacent to the Route 17 Bypass in Warrenton (Figure 1). It collects highway runoff from a bridge along the bypass with a drainage area of 809 m^2. Of the total bypass length, approximately 1.93 km is expected to drain into the Warrenton Reservoir. This BMP is one of many design control measures used to prevent degradation to the Warrenton Reservoir attributable to the bypass extension. The projected average daily traffic for the bypass is 15,810 vehicles (design year 2010) (Loos, 1996).

Figure 1. Isoilater Site: Route 17 Bypass, Warrenton

The Isoilater is a vault/reservoir structure with a storage capacity of 7.57 m^3, a maximum treatable flow rate of 0.018 m^3/s, a residence time of approximately 7 min, and an inlet pipe diameter of 46 cm (Americast, 1997). The oil grit separator is estimated to have a potential removal of 74% for TSS, 30% for chemical oxygen demand (COD), 13% for phosphates, and 53% for volatile solids (Yu et al., 1997). The particular model used has an oil holding capacity of 1.14 m^3, a sediment holding capacity of 4.69 m^3, a maximum treatable area of 5,706 m^2, and a maximum bypass flow rate of 0.453 m^3/s (Americast, 1997). The Isoilater was installed with the influent and effluent pipes in a straight-line configuration.

Another Isoilater, with a storage capacity of 3.785 m^3, was monitored in a previous study (Yu et al., 1999a). The unit was installed at the bus maintenance/parking lot for the City of Charlottesville in 1997 and monitored for 1 year. Information concerning the Charlottesville Isoilater is included in this study for comparison purposes.

The Isoilater is designed to treat the first flush flows of rainfall events and bypass higher flows by a hydraulic jump using a V-notch overflow plate. The unit consists of a fiberglass separator device housed in a conventional-diameter manhole. Beneath the separator device is the treatment tank. The unit operates under two conditions: full treatment and no treatment or partial treatment. The unit is designed to operate on a head differential across the device and the riser pipe. Because of patent infringements, the Isoilater is no longer available on the market. The Isoilater is identical in function with the Stormceptor.

Bioretention Area

The bioretention area was in the Monticello High School parking lot in Charlottesville (Figure 2). The area drains a 3,157-m^2 impervious section of the lot. The drainage area includes approximately 130 parking spots with seasonal occupancy variation. Vegetation at this site was sparse and immature at the time of field monitoring.

Figure 2. Bioretention Area: Monticello High School, Charlottesville

The bioretention area was constructed in the summer of 1998 following general guidelines for the bioretention design. Land constraints caused the actual size of the area to be reduced to less than the proposed size of 102 m^2. The area consists of six major functional components: grass buffer strip, ponding area, planting soil, sand bed, organic layer, and plant material (Prince George's County, 1993). The bioretention area is an off-line BMP designed to treat the first flush of runoff. Biological and physical mechanisms such as transpiration, evaporation, storage, and nutrient uptake occurring in the plant and soil matrix remove pollutants from runoff (Prince George's County, 1993).

A portion of the sheet flow from the parking lot is directed toward the area because of the gradual slope of the drainage area. The remaining flow is blocked by the curb and routed toward the outflow of the area where it combines with the outflow into the main stormwater drain. Runoff enters the bioretention area via three evenly spaced riprapped channels, which prevent large debris such as trash from entering the area. Bioretention areas are limited to small impervious watersheds of 4,047 m^2 or less.

Stormceptor

The Stormceptor is located on the bank of Stadium Road in Charlottesville on the UVA grounds (Figure 3). The unit collects drainage from the southeast parking lot of Scott Stadium along Stadium Road and Whitehead Road only. The drainage area is approximately 10,117 m^2. Because of the ongoing construction phase of the Scott Stadium expansion project, the unit was collecting primarily construction runoff during field monitoring. The BMP was sized for the post-construction phase of the expansion project as part of the overall stormwater management control program at Scott Stadium. The unit was installed underground during the early stages of construction and has been subjected to a representative hot spot setting.

Figure 3. Stormceptor: UVA's Scott Stadium, Charlottesville

The Stormceptor is an STC 3600 precast concrete model with a fiberglass disk insert. It has a total holding capacity of 13.8 m^3, a maximum sediment storage capacity of 9.77 m^3, and a maximum oil storage capacity of 3.33 m^3 (Stormceptor, 1999). The maximum flow rate without bypass is 0.029 m^3/s. From the guidelines provided by the manufacturer for the maximum impervious drainage area, the STC 3600 model series for this site is sized for 80% TSS removal in a sensitive area. Configuration of the effluent pipe is at 100 degrees with the influent pipe (because of existing site constraints), not the typical 180 degrees, which is the preferred configuration.

The Stormceptor is a vault/reservoir oil and grit separator that operates on a 2.54-cm head differential between the influent and effluent pipes. The unit operates under two conditions: normal flow and high flow. During normal flow, the U-shaped weir at the inlet creates a swirl affect and inflow is discharged into the treatment chamber, where it eventually reaches the outlet riser pipe. When the inflow exceeds the maximum treatable design flow rate, the system undergoes bypass and minimal to no treatment is provided under this condition. Oil, grease, and floatables are trapped under the fiberglass insert, and sediment settles to the bottom of the unit. The Stormceptor is identical in function with the Isoilater.

Vortechs

The Vortechs is located on the bank of the UVA Facility Management parking lot on Alderman Road in Charlottesville (Figure 4). The unit drains a 2,428-m^2 portion of a busy maintenance vehicle parking lot with a gas island. However, the unit does not collect drainage from the more congested section of the yard, which has heavy-duty vehicles, sand, salt, and trash piles. Drainage is limited to an impervious section of the parking lot where vehicles are only parked and refueled. Runoff collects near the center of the parking lot and enters through a steel grate where it then flows to the Vortechs. The Vortechs outflow flows directly into Meadow Creek, which has significant problems with the degradation of water quality.

Figure 4. Vortechs: Field Monitoring Location

A Vortechs Model 3000 was installed in November 1999. The unit has a peak design flow rate of 0.127 m^3/s, sediment storage capacity of 1.34 m^3, oil storage capacity of 1.89 m^3, and maximum holding volume of 11.36 m^3 (based on the design dimensions of the unit) (Vortechnics, 1999). The grit chamber volume is approximately 1.67 m^3 for sediment retention and settling. The unit is designed for a peak flow rate of 0.127 m^3/s for a 25-year design return period with an 80% removal efficiency for TSS. The Vortechs model monitored in this study was installed improperly. The influent pipe was installed at an angle less than 90 degrees with the grit chamber wall, deterring tangential flow. Vortechnics, the manufacturer of the Vortechs unit, examined the site. As a result of this examination and other field observations, a key installation problem was discovered near the conclusion of this study. The efficiency of the unit was significantly compromised as a result of the improper installation.

The Vortechs system is designed to treat all flows, without bypass of the unit. Its main feature of operation is the swirling motion created by the tangential inlet, which directs settable solids toward the center of the chamber when enough runoff momentum is present. Otherwise, during small storms, the grit chamber behaves like a detention tank with little or no swirl action. During storm events, the sediment is suspended in the circular flow path. The sediment settles back in the center of the grit chamber after the inflow has ceased. Oil, grease, and other floatables are trapped by the center baffle in the second chamber of the unit. The weir and orifice provide flow control during high flows when storm drains are flowing at peak capacity. During dry weather, the volume of water in the entire unit remains at a level just below the influent pipe.

Sampling Procedure

Storm event sampling was used to assess the pollutant removal of the BMPs at the various sites. Sampling setup locations were site specific and are discussed in further detail for each site. Samples from storm events satisfying the minimum EPA-recommended criteria of 72 h of prior dry weather conditions were collected for this experiment. Other criteria included a minimum rainfall depth of 25.4 cm.

American Sigma 900 MAX portable automatic samplers were used to collect samples automatically on a specified time cycle with simultaneous level, velocity, flow, and rainfall measurements. Samplers were specifically programmed for each site and triggered by rainfall and/or a rise in the water level to take a maximum of 24 samples for each sampling point per event. Rainfall and flow data were logged at a set time interval for each site by the automatic sampler. Rainfall data were logged by the sampler using a tipping bucket rain gage, and depth measurements for flow determination were logged by a pressure-sensitive transducer. Samples were automatically collected at the specified time interval by a high-speed peristaltic pump equipped with a Teflon-lined polyethylene or tygon intake line with a 0.95-cm inner diameter attached to a strainer. Sampling frequency ranged from 15- to 20-min intervals to allow the capture of samples from the entire storm event for each site. Logged data from each storm event were transferred using an American Sigma Data Transfer Unit and then interfaced with STREAMLOG or INSIGHT software for analysis and calculations.

Stormwater samples were primarily analyzed as flow-weighted composites. These are single samples intended to be representative of the water quality for an entire storm event. Composite samples were selected to reduce the number of samples and total cost for the project. An EMC was measured as the concentration in a flow-weighted composite, with the volume of each sample fraction directly proportional to flow at the time of sample collection. Composite sample analysis provided an average concentration of pollutants for the storm event. In addition, during particular storm events, discrete analysis was used to calculate EMCs. Oil and grease samples were analyzed only on a first flush basis. Samplers were programmed to take a separate sample of the initial storm runoff from the time-weighted samples in the beginning of the sampling program. First flush samples were taken 5 min after the stormwater sampling program was activated. For the Stormceptor and Vortechs sites, manual first flush oil and grease samples were taken.

Sediment sampling was performed to determine the accumulated sediment composition in the drainage system. Sediment samples and depth measurements were taken with a coretaker, which is a 488-cm-long clear polycarbonate tube with a check valve on one end. It is capable of measuring the thickness of the sludge blanket and extracting a core sample for determination of sediment and water column concentrations (Raven Environmental Products, Inc., 1999). Sediment samples from the various oil and grit separators were extracted with the coretaker apparatus for a composite analysis or a comprehensive screening for various semivolatile and volatile organics as well as metals. To collect a sample with the coretaker, the contents needed to be drained into a 0.0038-m^3 or larger bucket and then a smaller size sludge sample taken. This procedure was recommended by the manufacturer (Raven Environmental Products, Inc., 1999).

A composite scan for approximately 30 pollutants was performed on the extracted sediment by Central Virginia Laboratories Consultants. Samples were collected and preserved, when necessary, in accordance with the laboratory quality assurance/quality control protocol. Field samples were transported, by the field crew, to the UVA Stormwater Laboratory for physical and chemical analysis. Samples for oil and grease, sediment, and other constituents were released to Central Virginia Laboratories Consultants or Aqua-Air Laboratories for analysis. Because of the extensive sampling performed at each site, sample analysis had to be performed by private laboratories to meet the project objectives and time frame.

Laboratory Analysis

Analytical Parameters

Constituents analyzed were selected from the list of parameters recommended by the Nationwide Urban Runoff Program (EPA, 1991) to characterize urban runoff (Table 2). Stormwater analysis parameters selected for this project were TSS, COD, total phosphorus (TP), total nitrogen (TN), copper, zinc, and oil and grease. Insufficient funds and personnel were available for analysis of the other parameters listed in Table 2.

Table 2. Recommended Urban Runoff Analytical Parameters

Conventional Parameters	Nutrients	Metals	Biological Parameters
pH	Total phosphorus[a]	Copper [a]	Fecal coliform
Total suspended solids[a]	Soluble phosphorus	Lead	
Biological oxygen demand	Total kjeldahl nitrogen[a]	Zinc[a]	
Chemical oxygen demand[a]	Nitrate/nitrite nitrogen		
Settleable solids			
Temperature			

[a]Pollutants analyzed for this study.
Source: EPA (1991).

Pollutants can have significant effects on water quality and aquatic habitat. Excessive sediment can be detrimental to aquatic life by interfering with photosynthesis, respiration, growth, and reproduction. In addition, sediment can transport other pollutants that are attached to it including nutrients, trace metals, and hydrocarbons. The presence of nutrients, such as nitrogen and phosphorus, can result in excessive or accelerated growth of vegetation or algae, resulting in impaired use of water in lakes and other sources of the water supply. Oxygen-demanding substances depress the dissolved oxygen levels in streams, lakes, and estuaries. The COD of polluted water is a measure of the oxygen required to oxidize an organic matter in a waste sample using chromic acid, a strong chemical oxidant (Hauser, 1996). The COD is often used to determine the quality of water that either is not readily biodegradable or contains compounds that inhibit biological activity.

Oil and grease contain a wide array of hydrocarbon compounds, some of which are toxic to aquatic organisms at low concentrations. Heavy metals, such as lead, zinc, chromium, and copper, are of concern because they are toxic to aquatic organisms, can bioaccumulate, and have the potential to contaminate drinking water supplies. Highway runoff is characterized as being relatively high in heavy metals because of its association with vehicles and parts. Zinc often serves as a good indicator for the presence of metals, since it is found in many automobile engine and mechanical parts as well as automobile lubricants and fluids (Yu et al., 1993).

Laboratory Procedures

Stormwater samples for TP and COD were analyzed in accordance with the procedures in the *Hach DR/2000 Spectrophotometer Handbook* (Hach Company, USA, 1991). Quality assurance and quality control were assured by adherence to procedures detailed in UVA's *Stormwater Management Laboratory Manual* (Earles et al., 1999). The analyses of TP, COD, and TSS were performed as described in the *Standard Methods for the Examination of Water and Wastewater* (Eaton et al., 1995). Oil and grease and sediment analyses were performed by private laboratories. All analyses were performed in accordance with EPA laboratory procedures. Table 3 lists the analytical parameters and procedures used for this study.

Table 3. Analytical Parameters and Procedures

Parameter	Method	Procedure	MDL (mg/L)	Source/Analyst
TSS	Gravimetric	Standard Methods 2540D	2.5	Standard Methods for the Examination of Water and Wastewater, UVA
TP	Spectrophotometric	Hach Method 8190	0.10	Hach DR/2000 Spectrophotometer Handbook, UVA
		SM 4500B5E	0.01	
COD	Spectrophotometric	Hach Method 8000	3.0	Hach DR/2000 Spectrophotometer Handbook UVA and Central Virginia Laboratories Consultants
TN	Ammonia as N	EPA 350.3	0.1	Central Virginia Laboratories Consultants
	Total kjeldahl nitrogen	EPA 351.3	0.1	
Copper	Total copper	EPA 220.1	0.020	Central Virginia Laboratories Consultants
Zinc	Total zinc	EPA 200.7	0.005	Central Virginia Laboratories Consultants
Oil and Grease	Freon extraction	Standard Method 503-A	1.0	Aqua Air Laboratories, Charlottesville, VA
	N-hexane extraction	EPA Method 1664	5.0	EPA-821-R-98-002 Central Virginia Laboratories Consultants
Sediment Analysis	Inorganic Constituents	SW7040, SW7060, SW6010B SW7210, SW7470	vary by method	Central Virginia Laboratories Consultants
	Organic Constituents	SW8081, SW8151, SW8270C, SW 8260B		

Data Analysis and Presentation

The efficiency ratio method was used to analyze monitored BMP field data and to determine the study period removal efficiency (PRE). The PRE was defined as:

$$\text{PRE} = 1 - \frac{\text{Average outlet EMC}}{\text{Average inlet EMC}} \qquad \text{[eqn.1]}$$

Average inlet and outlet EMCs of pollutants over the study monitoring period were calculated for each BMP [eqn. 2] as:

$$\text{Average EMC} = \frac{\sum_{j=1}^{m} \text{EMC}_j}{m} \qquad \text{[eqn. 2]}$$

where *m* = number of events measured. The EMC was measured as a flow-weighted composite sample with the volume of each fraction directly proportional to the flow at the time of collection. This method weighs EMCs from all storms equally regardless of the relative magnitude of the storms. For example, a high-concentration/high-volume event has the same weight in the average EMC as a low-concentration/low-volume event (URS et al., 1999).

An average efficiency of individual storm loads method was also used for comparative purposes (eqn. 3):

$$\text{Average individual storm load removal efficiency} = \frac{\sum_{j=1}^{m} \text{Storm efficiency}_j}{m} \qquad \text{[eqn. 3]}$$

$$\text{where Storm efficiency} = 1 - \frac{\text{Load}_{out}}{\text{Load}_{in}} = 1 - \frac{\text{EMC}_{out} \times V_{out}}{\text{EMC}_{in} \times V_{in}}$$

and *m* = number of events measured. This method is a mass balance method of individual storm loads that assumes the influent volume is equal to the effluent volume for each storm event. Storm sizes and other factors do not play central roles in the computation of the average efficiency of the BMP. In addition, a standard deviation (SD) was calculated to determine the variability of the sample set around the mean value. The SD shows the BMP removal efficiency variation with respect to storm size. Data analysis using the efficiency ratio method along with a comparative individual storm load removal efficiency method was performed for the Isoilater, Stormceptor, and Vortechs.

In instances where data analysis could not be performed using EMCs, the storm efficiency was determined using mean concentrations [eqn. 4]:

$$\text{Storm removal efficiency}_{MC} = 1 - \frac{\text{Average outlet concentration}}{\text{Average inlet concentration}} \qquad \text{[eqn. 4]}$$

This method assumes that the flows from the samples taken are indicative of the overall event. Individual samples are weighted equally, and the storage capacity of the BMP is not accounted for. The bioretention area typically has a smaller volume of outflow than inflow, and on a mass basis, this affects removal. Therefore, the mean concentration method provides a more conservative removal efficiency than a mass-based method. The mean concentration efficiency method was applied only to evaluate the performance of the bioretention area where flow-weighted data were not available. Further data limitations, especially the number of influent and effluent samples successfully collected per storm event, precluded the calculation of a representative average of all storm efficiencies to be calculated. Instead, the PRE for the bioretention area was calculated using eqn. 5:

$$PRE = 1 - \frac{\sum_{j=1}^{m} \text{Average outlet concentration}}{\sum_{j=1}^{m} \text{Average inlet concentration}} \quad \text{[eqn. 5]}$$

where m = number of events measured. The time that influent and effluent samples were collected during storm events was very inconsistent. Most samples were collected during the first flush for storms, where concentrations are expected to be much higher. Samples taken during the duration of the storm were very limited. Therefore, the average concentration removal efficiency for each storm was very limited. In addition, SDs for the average concentration removal efficiencies for each storm were calculated to show the variability of the data.

RESULTS AND DISCUSSION

Stormwater Sampling

Isoilater Results

Seven storms were sampled from May 1999 through October 1999. Only three storm events were sampled completely where both corresponding influent and effluent samples were collected successfully. Data were limited because the sampling equipment failed frequently. The Warrenton Isoilater was located 2 hours away from UVA, which made checking sampling equipment during storm events to troubleshoot problems difficult. Previous monitoring data from a study conducted from October 1997 and September 1998 were incorporated for comparison and BMP evaluation. Event mean flowweighted composites were analyzed for TSS, TP, and COD to determine EMCs. Oil and grease was analyzed on a first flush basis only. All water quality parameters monitored at this site had positive PREs: TSS 73%, TP 33%, COD 70%, and oil and grease 69% (Figure 5). The TSS PRE compared well with the TSS design removal efficiency of 73.3%. The PREs for TP, COD, and oil and grease were much higher than the predicted laboratory estimates of 13%, 30%, and 53%, respectively (Yu et al., 1997).

The average influent EMCs for TSS, TP, COD, and oil and grease were within the expected ranges for highway runoff. Effluent flow rates were relatively low, indicating the effectiveness of the Isoilater in reducing runoff velocities and preventing further erosion. No bypass storms were sampled during the study monitoring periods where the influent flow rate exceeded 0.453 m^3/s as specified by the manufacturer.

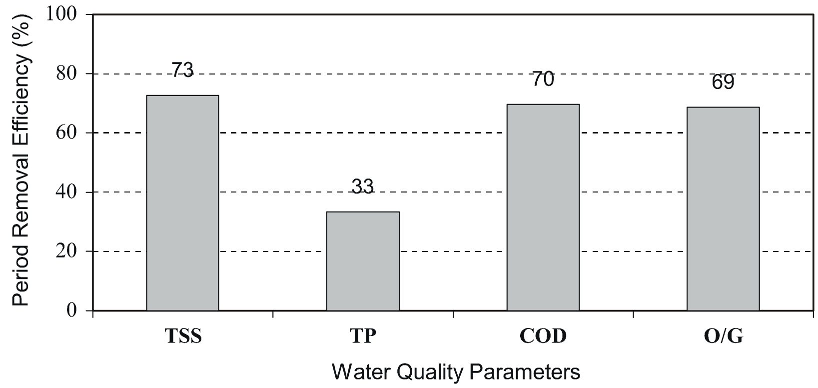

Figure 5. Isoilater: Period Removal Efficiency

In general, when the two monitoring periods were compared, higher influent EMCs for the earlier monitoring period produced higher removal efficiencies than for the later one because of the prominent erosion problem caused by the newly built bypass route. The results are site specific because of the design specifications of the unit and runoff characteristics of the site during each of the monitoring periods, which is discussed in detail in a later section.

Total Suspended Solids

A variety of storms ranging from 3.8 to 64.8 mm were sampled from October 1997 through October 1999. Figure 6 shows the influent and effluent EMCs for TSS. Based on the storms sampled, the cumulative rainfall depth did not correlate with the reported TSS individual storm load removal efficiencies, which were high for all storm sizes. An average individual storm load removal efficiency of 71% was calculated for TSS with an SD of 12.06, which compares well with the TSS PRE of 73%. The average individual storm load removal efficiency indicates the average of all storm removal efficiencies reported and is more sensitive to the variation of individual storm removal efficiencies. For this site, the average TSS individual storm load removal efficiency and the TSS PRE compared well. Therefore, individual storm removal efficiencies for TSS were expected to be relatively high.

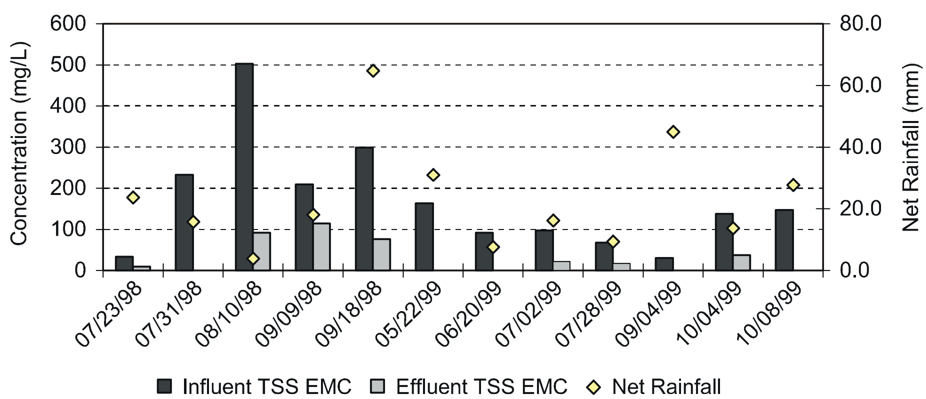

Figure 6. Isoilater: Event Mean Concentrations for Total Suspended Solids

No trend was expected with influent EMCs and corresponding antecedent dry days because the concentration of runoff contaminants varies during storm events because of changes in rainfall intensity throughout the storm and the initial quick washing of the contaminants deposited during the antecedent dry period. Though the accumulation of pollutants increases with the increase of the number of dry days, previous studies (Stotz, 1987) determined that the wind movement associated with moving vehicles was responsible for blowing away the accumulated pollutants to the side of roadways. Studies (Ellis et al., 1984) regarding the antecedent dry period have concluded that pollutant loads do not increase proportionally with such periods.

Total Phosphorus

The main mechanism for pollutant removal in the Isoilater is detention. Reactive phosphorus is known to sorb strongly to fine-grained particles (Chapra, 1997). Figure 7 shows the influent and effluent EMCs for TP. During the initial monitoring of the Isoilater beginning in October 1997, the site exhibited a lot of erosion because of the newly built bypass as evident from the high influent TSS EMCs, which ranged from 34 to 503 mg/L. Samples were extremely sludgy, and the amount of small particulates present in the runoff increased from erosion. The TP PRE (56%) for the first monitoring period was reported to be relatively high compared with that (17%) for the second monitoring period (April 1999 through October 1999). The influent TSS EMCs for the second period were much lower and ranged from 31 to 164 mg/L. Higher TP removal was expected for the first monitoring period because more clay particulates were present in the runoff. TP would sorb more to these fine particles and settle out in the Isoilater. The Isoilater was sized with significant excess storage capacity (7.57 m^3) to serve only an 809-m^2 watershed. Therefore, the unit had a longer detention of runoff during storm events, which increased the removal of fine particulates such as clay for small to medium storms.

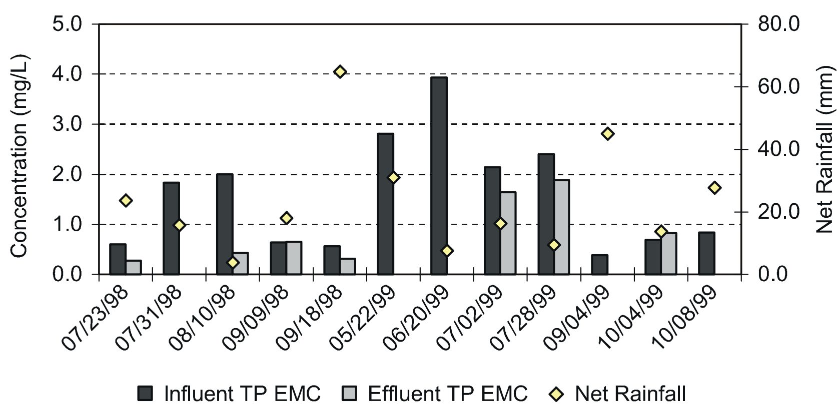

Figure 7. Isoilater: Event Mean Concentrations for Total Phosphorus

Chemical Oxygen Demand

Figure 8 shows the influent and effluent EMCs for COD. The COD PREs for both monitoring periods were approximately the same: 68.5% for the first period and 70.8% for the

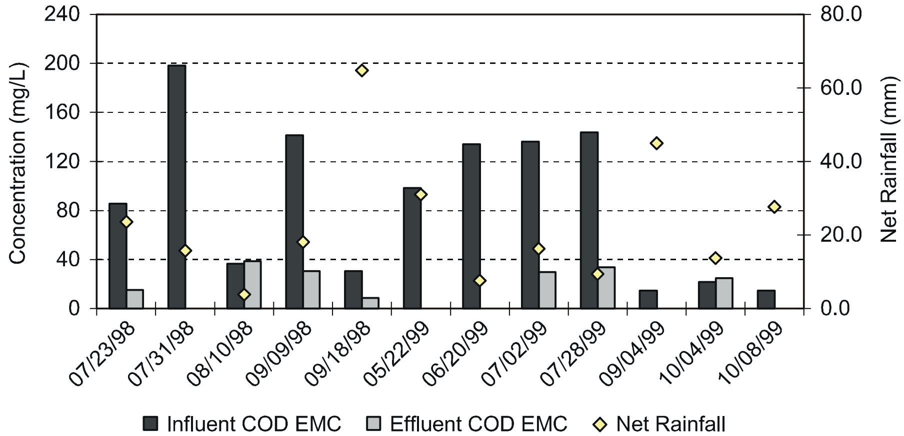

Figure 8. Isoilater: Event Mean Concentrations for Chemical Oxygen Demand

second. COD is independent of TSS concentration or removal. The COD influent EMCs for the first monitoring period (average = 58.8 mg/L) were slightly higher than for the second period (average = 43.0 mg/L). Although net rainfall did not seem to have a significant effect on TSS PREs, influent COD EMCs were much higher for small storm events, those less than 25.4 mm, and corresponding COD individual storm load removal efficiencies were high as well. An average individual storm load removal efficiency of 52.6% for both monitoring periods was calculated for COD, with an SD of 42.5, which shows there is variability in the individual storm load removal efficiencies because of the depth of the rainfall.

Oil and Grease

Oil and grease removal efficiency data were very limited because of the difficulty in measuring oil and grease removal. Figure 9 shows the influent and effluent first flush oil and grease concentrations. However, a first flush approach yielded relatively high removal efficiencies. Again, higher oil and grease removal efficiencies were reported for the first monitoring period than the second because of the increase in sludge content, which was validated by Aqua Air Laboratories. Oil and grease exists in both particulate and emulsion form because it

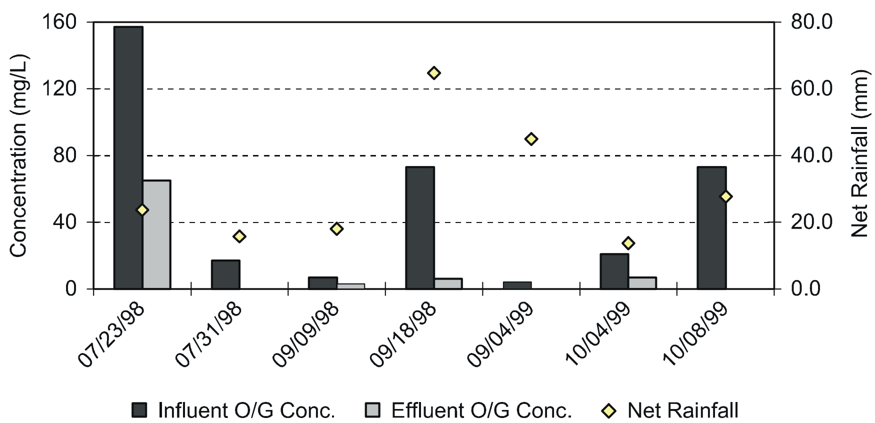

Figure 9. Isoilater: First Flush Oil and Grease Concentrations

adheres to the soil particulates and is immiscible with water. The SD for the oil and grease removal efficiency was 16.1 for both monitoring periods, indicating no significant dependency of oil and grease removal on rainfall depth because samples were taken during the first flush of the storm.

Bioretention Area

The bioretention area was monitored from September 1999 through November 1999. Arithmetic mean influent and effluent concentrations were used to characterize the pollutant removal benefits of the area because corresponding storm flow data were unavailable. The results are conservative because removal would be expected to be higher if influent and effluent mass loadings were used to determine pollutant removal. The runoff is stored in the planting soil, where it discharges over a period of days to the in-situ material underlying the bioretention area, which decreases outflow (Prince George's County, 1993). Based on the arithmetic mean PREs calculated, the removal efficiencies for the storms sampled were TSS 53%, TP 13%, COD 16%, and oil and grease 66% (Figure 10).

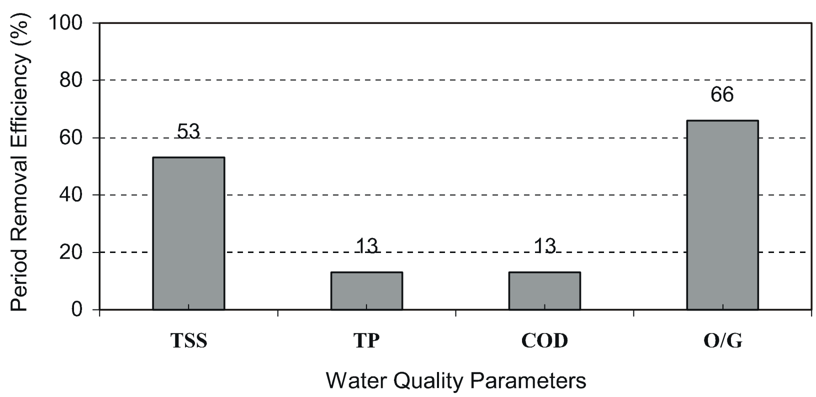

Figure 10. Bioretention Area: Period Removal Efficiency

Influent runoff consisted of an orange clay. Even though the drainage area is an impervious parking lot, erosion was evident. Effluent samples for some storm events were noted during TSS analysis to consist of orange clay and dark dirt particulates. Two possible interferences could have had a significant impact on the monitoring results. The bioretention areas could have leached clay particulates, and dirt or additional particulates could have entered the area before the sampling point from the steel grate just above the sampling point, although runoff was not observed to be entering at this point during sampling. Another factor that could have contributed to the low PRE was the immaturity of the vegetation. The vegetation was sparse and very young during monitoring, which would make it difficult to mimic a mature forest nutrient cycle. Water quality benefits are expected to be optimal in a more densely planted and mature area. Typical removal efficiencies reported for bioretention areas are TSS 75%, TP 59%, TN 50%, and metals 75% to 80% (FHWA, 1999).

The bioretention area has an estimated 6-h detention time as observed during field sampling. The minimum size storm observed to produce outflow for the area during the monitoring period was 9.1 mm. Smaller storms may not have produced outflow because of the storage capacity of the area. For small storms that do not produce outflow, 100% removal is achieved by the bioretention area. The effluent depth sensor trigger was set to detect a depth change of less than 0.51 cm. The outflow was always very small, indicating the area's effectiveness in reducing effluent runoff velocities.

Total Suspended Solids

Figure 11 shows the influent and effluent average concentrations of TSS. The average influent concentrations varied between 10 and 152 mg/L. The average effluent concentrations varied between 30 and 104 mg/L. The SD of the mean concentration removal efficiencies for TSS (119.0) showed the significant variation of the storm event removal efficiencies. This suggests that TSS removal efficiencies varied with net rainfall. Two of the three larger storms (near 25.4 mm or greater) that had corresponding outflow data had negative TSS removal, and small to medium storms had positive removal. Previous monitoring results from Yu and Zhang (1999b) showed that two storm events of 29.2 mm and 25.2 mm had calculated arithmetic mean concentration removal efficiencies of -32% and -14%, respectively.

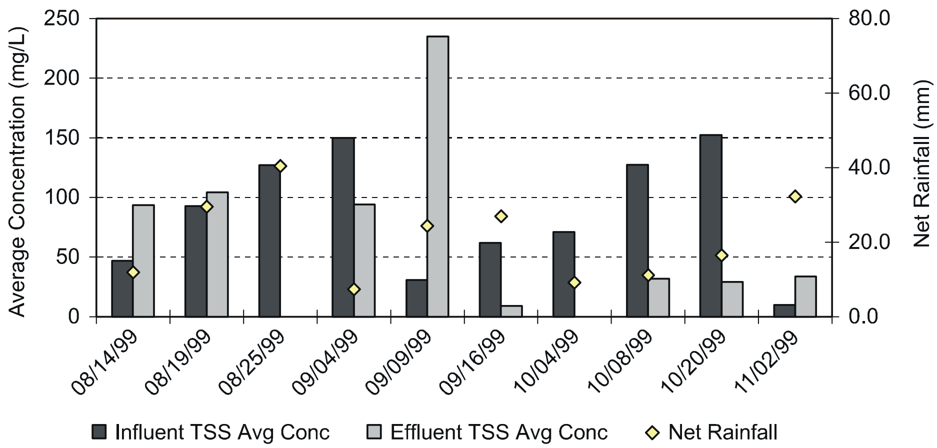

Figure 11. Bioretention Area: Average Concentrations of Total Suspended Solids

Total Phosphorus

Figure 12 shows the influent and effluent average concentrations for TP. Despite the potential contributing factors that may have affected the data, the TSS and TP PREs correlate well. For this site, the presence of fine-grained particulates such as clay in the outflow would decrease TP removal because effluent TP concentrations would be higher because of sorption of phosphorus to the finer clay particulates. TP mean concentration removal efficiencies were variable (SD = 30.84). Because of the sorption properties of reactive phosphorus, this was expected.

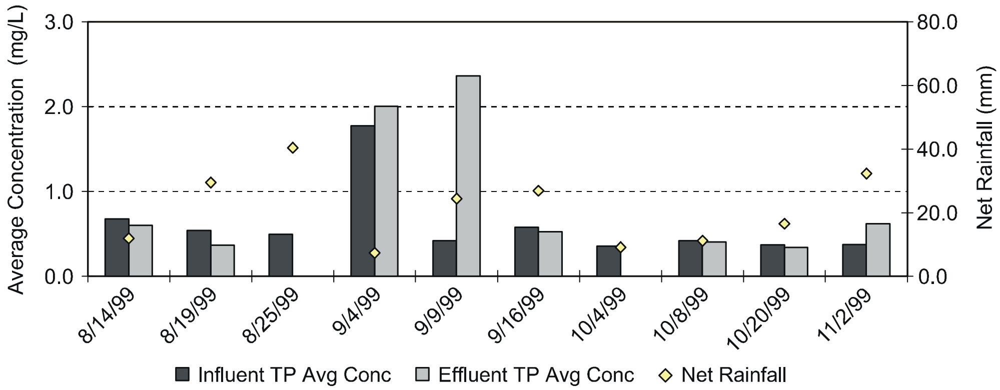

Figure 12. Bioretention Area: Average Concentrations of Total Phosphorus

Chemical Oxygen Demand/Oil and Grease

Figure 13 shows the influent and effluent average concentrations for COD. The highest mean concentration removal efficiency (50.4%) occurred for a small-to-medium storm of 11.2 mm (4/8/99). Mean concentration storm removal efficiencies showed less variability, with an SD of 24.47. In addition, oil and grease data were very limited. Figure 14 shows the influent and effluent first flush oil and grease concentrations. Only one storm event showed significant oil and grease removal. All other data remained fairly close to the method detection limit (MDL) for both influent and effluent samples. Therefore, it cannot be assumed that the bioretention area is effective in trapping oil and grease because both the influent and effluent concentrations are close to the MDL.

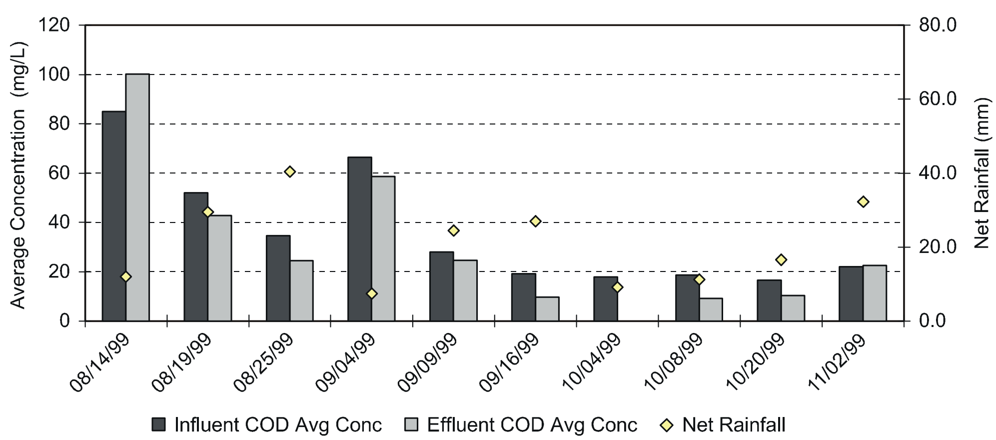

Figure 13. Bioretention Area: Average Concentrations for Chemical Oxygen Demand

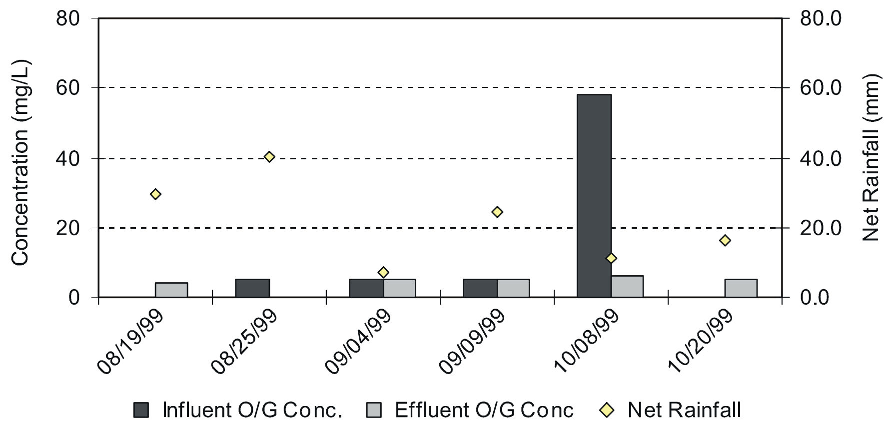

Figure 14. Bioretention Area: First Flush Oil and Grease Concentrations

Stormceptor

The Stormceptor was monitored from November 1999 through April 2000. The winter season was not monitored because the cold weather would have damaged the expensive equipment. Six storms were sampled for TSS, TP, COD, TN, copper, zinc, and oil and grease. All water quality parameters showed positive PREs (Figure 15) with the exception of TN (TSS 57%, TP 66%, COD 28%, TN 27%, copper 22%, zinc 73%, and oil and grease 33%). The unit was designed for 80% TSS removal. The removal efficiency ranges reported by the manufacturer without site-specific consideration were TSS 52% to 93%, TP 18% to 36%, total kjeldahl nitrogen 51%, and metals 21% through 52% (Stormceptor, 1999).

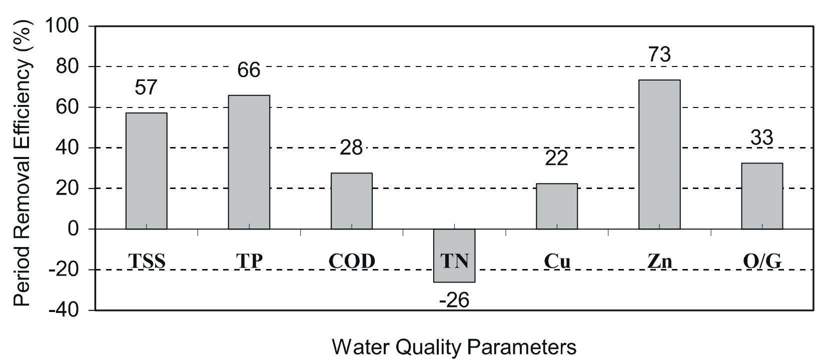

Figure 15. Stormceptor: Period Removal Efficiency

Total Suspended Solids

Figure 16 shows the influent and effluent average concentrations for TSS. The TSS PRE was below the expected design removal efficiency of 80%. The corresponding average TSS individual storm load removal efficiency for the monitoring period was 48%, with an SD of 27.8, which is lower than the PRE. The deviation may be explained by the effect of rainfall depth on the individual storm load removal efficiencies for TSS. The storm dated 3/20/00 with a rainfall

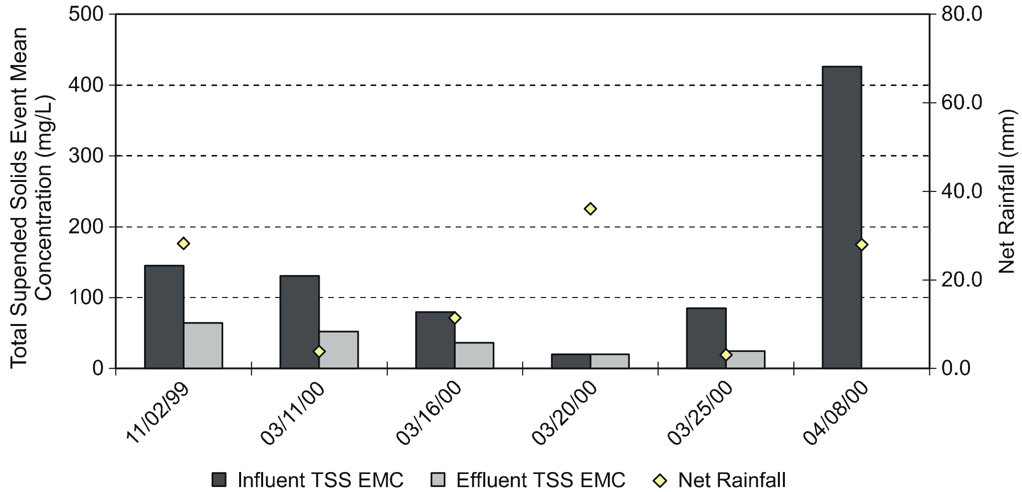

Figure 16. Stormceptor: Event Mean Concentrations for Total Suspended Solids

depth of 36.1 mm had the same influent and effluent TSS EMCs. As a result of field observations and removal efficiency data, it was determined that the unit had undergone bypass during this storm event. The event was also the largest storm sampled during the monitoring period. The unit showed the highest TSS removal for the two smallest storms of 3.8 and 3.1 mm, with corresponding TSS individual storm load removal efficiencies of 60% and 71%. Influent TSS EMCs ranged from 20 to 426 mg/L. It is important to note that the unit was designed to collect drainage from a 10,117-m^2 watershed after construction has been completed, which would decrease the TSS pollutant loadings and characteristics. Therefore, pollutant removal efficiencies would be expected to change. TP removal would be expected to decrease, and TN removal would be expected to increase.

Total Phosphorus

The TP PRE for the Stormceptor was high, which was expected because the runoff particulates for this site are primarily clay because of the erosion caused by the construction. Figure 17 shows the influent and effluent average concentrations for TP. The highest TP individual storm load removal efficiency (93%) occurred when the TSS individual storm load removal efficiency was highest (60%). TP removal correlated well with TSS removal; even when the system was undergoing bypass, there was still some reduction in TP (13%). TP removal was highest for the two smallest storms sampled and was considerably lower for medium-to-large storms. Because of the limited storage capacity of the Stormceptor per impervious area served, volumes for medium-to-large storms can exceed the BMP storage capacity and settling of particles during a storm is limited because of the short detention time. Small storm volumes are near the storage capacity of the BMP, circumventing this problem and allowing for additional settling between storm events.

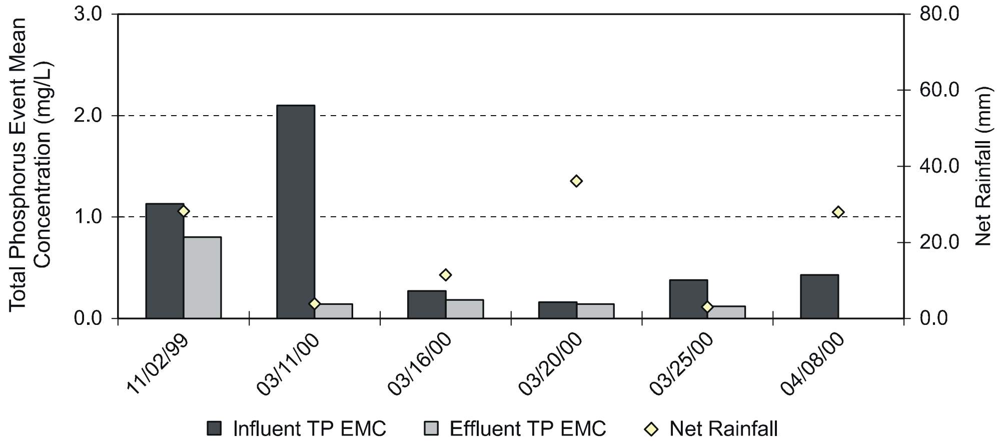

Figure 17. Stormceptor: Event Mean Concentrations for Total Phosphorus

Chemical Oxygen Demand

Figure 18 shows the influent and effluent average concentrations for COD. The COD PRE was low. The highest COD individual storm load removal efficiency (57%) occurred for a small storm event (3.1 mm) that did not undergo bypass. This also seems to follow the trend for the previous monitoring sites in this study. The increase in the influent COD EMCs for short storms can be attributed to the increase in oxidizable matter attributable to the first flush. Small storms consist primarily of the first flush of runoff because of their short duration. For larger storms, a dilution effect would be factored into the influent COD EMCs, causing the concentrations to decrease.

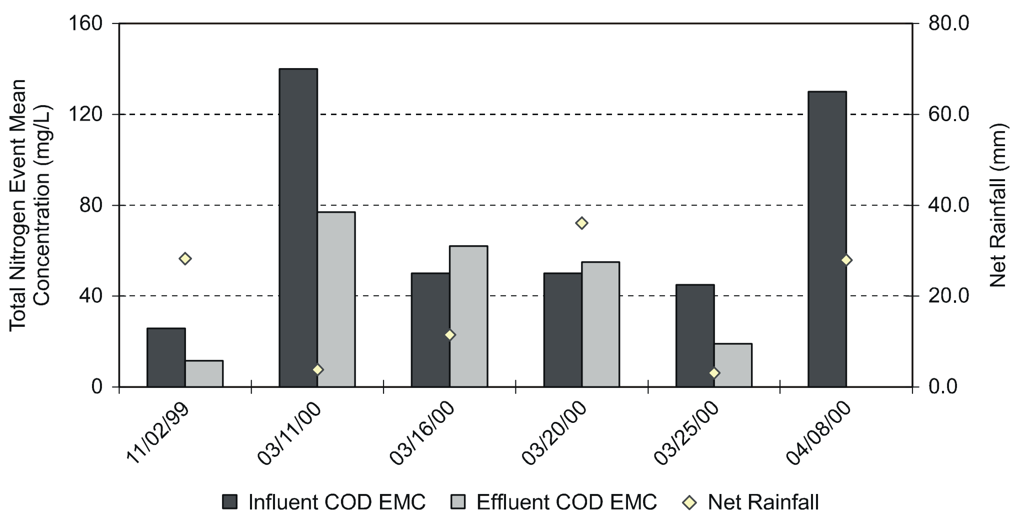

Figure 18. Stormceptor: Event Mean Concentrations for Chemical Oxygen Demand

Total Nitrogen

Figure 19 shows the influent and effluent average concentrations for TN. The TN individual storm load removal efficiency was negative for all storms with the exception of the storm dated 3/25/00, which varied in size and duration (SD = 126.34). No trend could be seen. Storms of 3.8 mm, 11.4 mm, and 36.1 mm had TN removal efficiencies of -25%, -242%, and -77%, respectively. However, the highest influent TN EMC corresponded to the smallest storm sampled (3.1 mm). The negative removal efficiencies can possibly be attributed to the decrease in aeration inside the BMP, which would limit the oxidation of ammonia. Another possible contribution would be the ammonia fixation of clay minerals. Clay is capable of retaining considerable amounts of NH_4^+ in nonexchangeable forms (Stevenson et al., 1999). It is possible that the increased aeration of the influent runoff could cause oxidation. Once the runoff enters the BMP, ammonia can become trapped by clay particulate fixation, causing effluent TN EMCs to increase. Detention for short storms would be longer, increasing clay removal by settling. The pH and microbial interactions could also be factors. Because of the complexity of the nitrogen cycle and the variable site conditions, other factors could have affected the TN individual storm load removal efficiencies and the overall TN PRE.

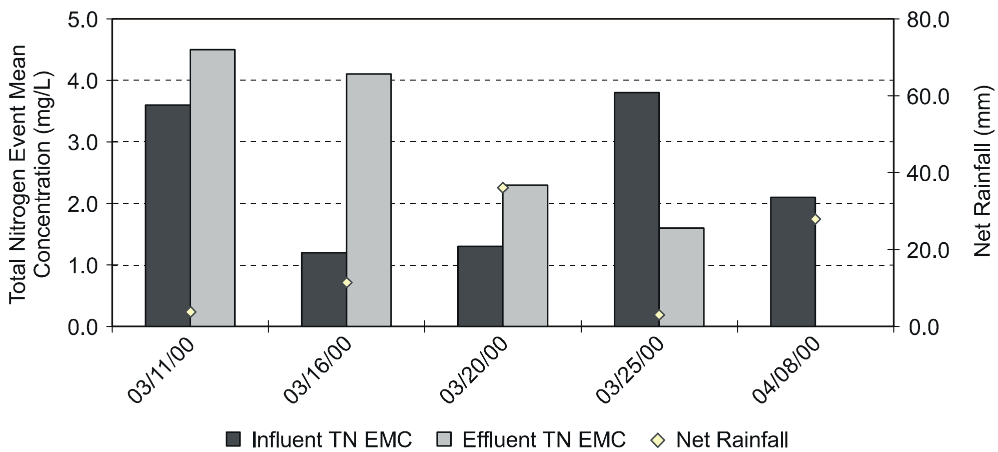

Figure 19. Stormceptor: Event Mean Concentrations for Total Nitrogen

Copper and Zinc

Figures 20 and 21 show the influent and effluent average concentrations for copper and zinc. The zinc PRE (73%) was much higher than the copper PRE (22%) and compared well with the TSS PRE. Copper has a much higher solubility than zinc based on metal solubility rules. Copper dissolves in the runoff, and zinc binds itself to the sediment in the runoff, which increases the removal of zinc by settling. The SDs for the individual storm load removal efficiencies for TSS, TP, and zinc were similar, indicating similar variability in individual storm load removal efficiencies attributable to rainfall depth and the interdependency of TP and zinc removal on TSS removal. Because of the limited detention time of stormwater runoff in the unit during storms, copper removal would be expected to be low. The unit is designed to separate sediment and grease during storm events. The possible increased detention between storm

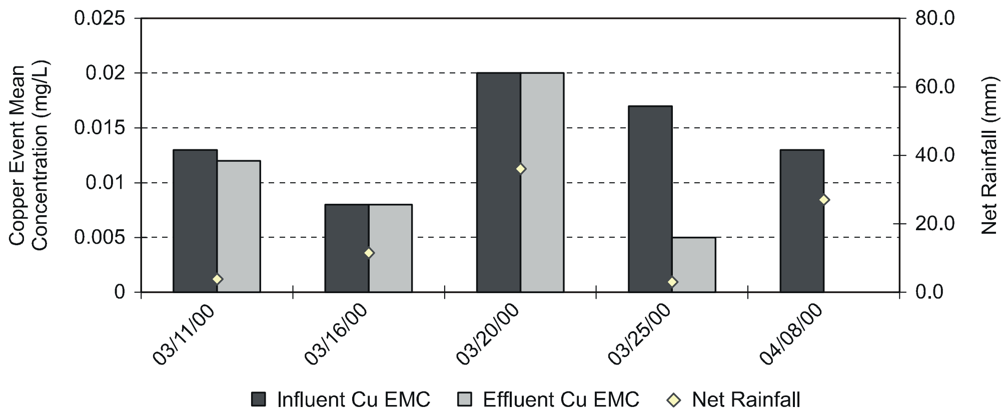

Figure 20. Stormceptor: Event Mean Concentrations of Copper

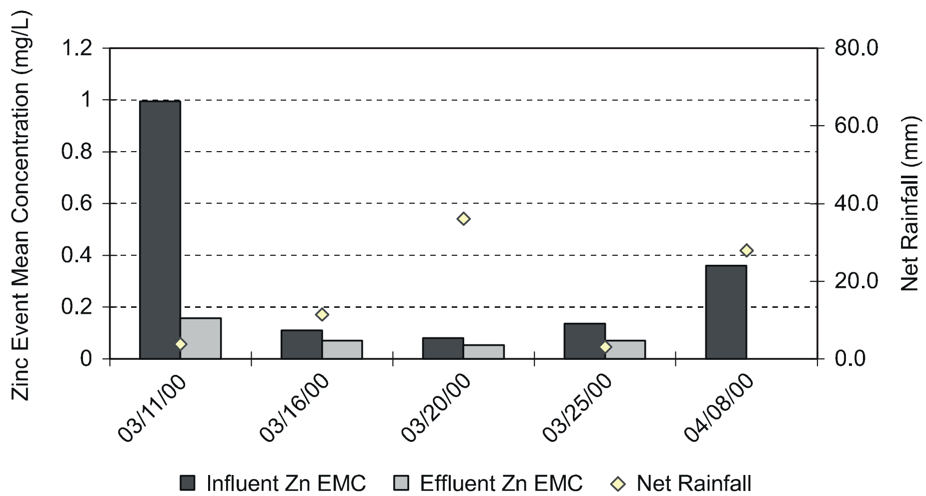

Figure 21. Stormceptor: Event Mean Concentrations of Zinc

events during antecedent dry days would enhance copper individual storm load removal efficiencies by allowing copper to precipitate and sorb to the sediment.

The copper influent and effluent EMCs for all storms sampled were below the EPA's drinking water standard of 1.3 mg/L. However, the effluent copper EMCs for three storm events exceeded the chronic toxicity of 0.0058 mg/L, and those for two storms exceeded the acute toxicity level of 0.0084 mg/L. Chronic toxicity testing reveals the ability of a substance to cause deleterious effects to living organisms during long-term exposure, and acute toxicity testing reveals the ability of a substance to cause deleterious effects to living organisms during short-term exposure. Further, all effluent zinc EMCs were below the EPA's secondary drinking water standard of 5.0 mg/L. The effluent zinc EMC for only one storm event exceeded the zinc acute toxicity standard of 0.18 mg/L, and all effluent zinc EMCs exceeded the chronic criteria of 0.047 mg/L. Use of the EMC for evaluating toxicity impacts is very conservative because it is an average concentration representing the entire storm event. Events during antecedent dry days would enhance copper individual storm load removal efficiencies by allowing copper to precipitate and sorb to the sediment.

The copper influent and effluent EMCs for all storms sampled were below the EPA's drinking water standard of 1.3 mg/L. However, the effluent copper EMCs for three storm events exceeded the chronic toxicity of 0.0058 mg/L, and those for two storms exceeded the acute toxicity level of 0.0084 mg/L. Chronic toxicity testing reveals the ability of a substance to cause deleterious effects to living organisms during long-term exposure, and acute toxicity testing reveals the ability of a substance to cause deleterious effects to living organisms during short-term exposure. Further, all effluent zinc EMCs were below the EPA's secondary drinking water standard of 5.0 mg/L. The effluent zinc EMC for only one storm event exceeded the zinc acute toxicity standard of 0.18 mg/L, and all effluent zinc EMCs exceeded the chronic criteria of 0.047 mg/L. Use of the EMC for evaluating toxicity impacts is very conservative because it is an average concentration representing the entire storm event.

Oil and Grease

Oil and grease data were limited, and a PRE of 28% was reported. Figure 22 shows the influent and effluent first flush oil and grease concentrations. When observed from the vent pipe, the unit did appear to be trapping oil and grease. Sometimes, a sheen of grease was observed on the top of the effluent riser pipe, indicating that oil and grease were also being released. The unit has a good potential for trapping large accidental fuel or oil spills, which would otherwise discharge into receiving waters. Even though this unit is operating under construction conditions, PREs were generally high for the Stormceptor during this study. This suggests that the unit is providing water quality benefits to some degree and should be incorporated in the construction site erosion and pollution prevention plan.

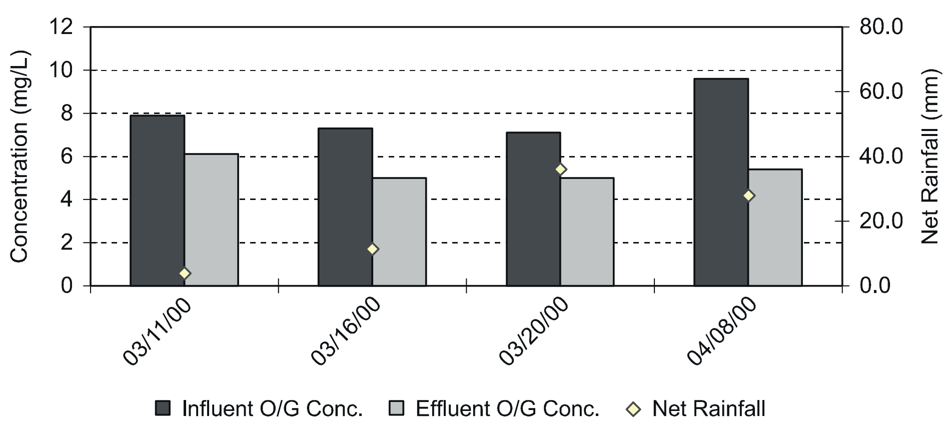

Figure 22. Stormceptor: First Flush Oil and Grease Concentrations

Vortechs

Seven storm events were sampled from this unit from March 2000 through April 2000. Water quality parameters monitored included TSS, TP, COD, TN, copper, zinc, and oil and grease. All water quality parameters showed positive PREs: TSS 27%, TP 11%, COD 24%, TN 64%, copper 13%, zinc 41%, and oil and grease 6%. The unit was designed for a TSS removal of 80%. The TSS removal efficiency reported by the manufacturer ranged from 80% to 84%, without site-specific consideration. Nutrient and metal removal efficiencies were not available.

Because of interference at the influent sampling point, which caused an increase in influent EMCs for the storms sampled on 3/25/00, 4/4/00, and 4/8/00, the influent EMC concentrations were adjusted to reflect an 84.5% reduction in the concentrations for these storms. Figure 23 shows the PRE for all water quality parameters monitored with the correction factor. The storm on 3/11/00 was omitted from the PRE calculation as a possible outlier. For analysis purposes and further discussion of results, only adjusted data were used. The influent pipe misalignment was confirmed by Vortechnics at the end of the monitoring study. The Vortechs is a flow-through device, and detention is not the main feature of the unit. The swirl effect created by the tangential influent flow is the principal feature of the unit, which was not observed during the study period.

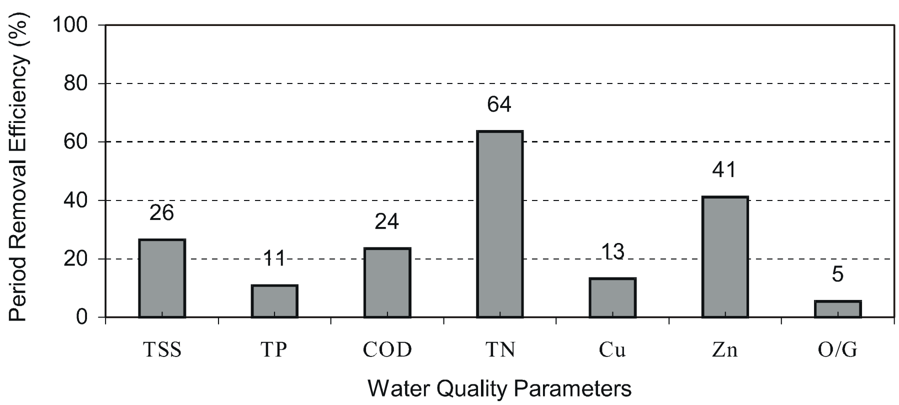

Figure 23. Vortechs: Period Removal Efficiency

Total Suspended Solids/Total Phosphorus/Zinc

Figures 24 and 25 show the influent and effluent EMCs for TSS and TP. Despite the contributing factors that affected the results, the TP, zinc, and TSS PREs compared well. This would be expected because these constituents tend to sorb to fine-grained particulates. Overall TP and zinc influent EMCs would be expected to be much less at the Vortechs site than at the Stormceptor site because of the different runoff characteristics and increased erosion at the Stormceptor site. Since the Stormceptor unit collected primarily clay particulates, influent TP EMCs (2.10 to 0.27 mg/L) were much higher than at the Vortechs site (0.880 to 15 mg/L). Further, influent TSS EMCs for the Stormceptor were associated with higher corresponding influent TP EMCs, whereas influent TSS EMCs for the Vortechs were associated with lower corresponding influent TP EMCs. In addition, the effluent TP EMCs were higher for the Vortechs than for the Stormceptor. The SD (71.9) of the TSS individual storm load removal efficiencies indicated a significant degree of variability. Since the Vortechs is a flow-through device, peak or high flows receive minimal treatment, if any. Large storms typically would

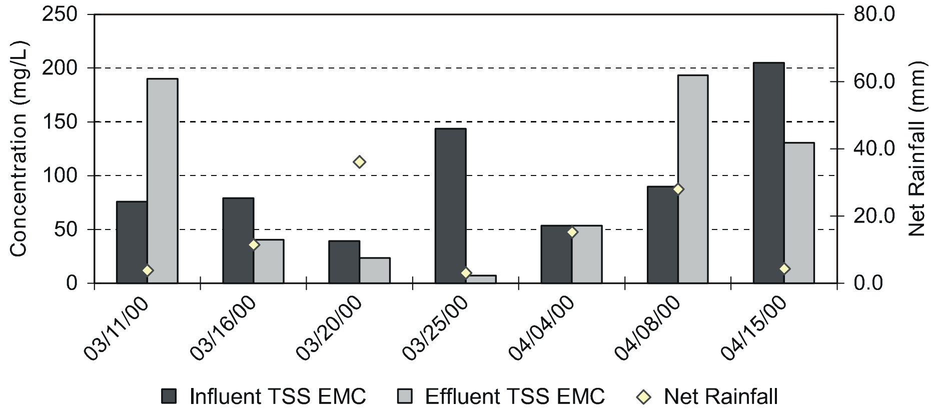

Figure 24. Vortechs: Event Mean Concentrations of Total Suspended Solids

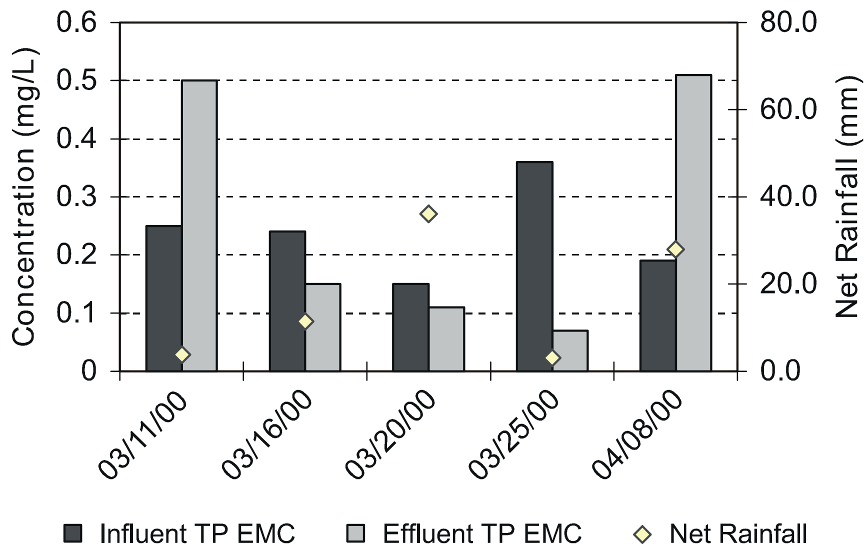

Figure 25. Vortechs: Event Mean Concentrations of Total Phosphorus

receive less treatment. The two largest storms (greater than 25.4 mm) considered for data analysis had low TSS individual storm load removal efficiencies.

Chemical Oxygen Demand/Total Nitrogen

Figures 26 and 27 show the influent and effluent EMCs for COD and TN. Influent COD EMCs were much higher for small storm events (less than 25.4 mm), and the highest COD removal efficiency (95%) occurred for the smallest storm sampled (3.1 mm). TN individual storm load removal efficiencies were positive for all storms sampled with the exception of the storm on 4/8/00. In contrast to the Stormceptor, the Vortechs is vented inside because the height of the permanent water in the unit remains up to only the dry-weather level, which is just below the influent pipe. During storm events, the BMP is rarely completely full; only during a peak

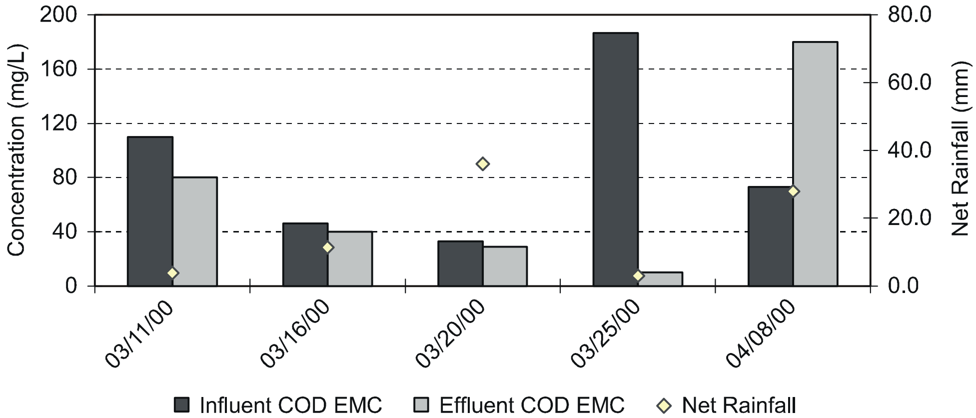

Figure 26. Vortechs: Event Mean Concentrations for Chemical Oxygen Demand

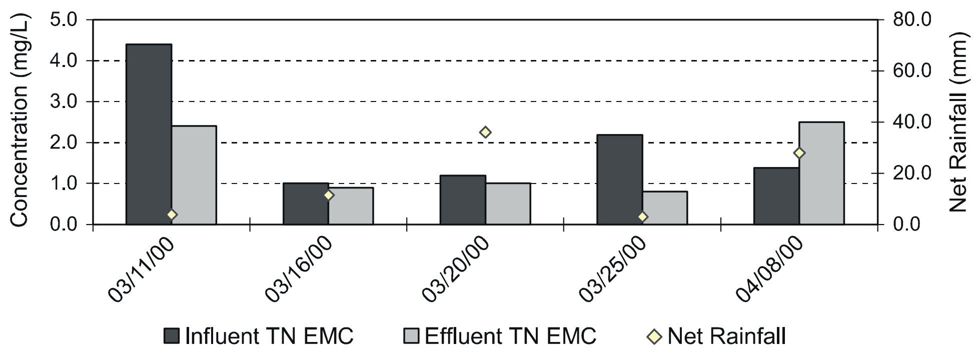

Figure 27. Vortechs: Event Mean Concentrations of Total Nitrogen

25-year storm would the unit be filled to capacity. Effluent TN EMC ranges for the Vortechs were much lower than for the Stormceptor. Possibly, the positive TN removal efficiency can be attributed to the increased aeration inside the BMP, which would increase the oxidation of ammonia and simulate air stripping treatment. Average influent TN EMCs for the Vortechs and Stormceptor units had a relative SD of only 16%, suggesting further that removal may have been affected by the function of the BMP.

Copper/Zinc/Oil and Grease

Metal influent and effluent EMCs were well below the EPA's drinking water standards. Effluent copper EMCs exceeded the EPA's chronic criteria during four storm events and the acute criteria during three. Effluent zinc EMCs exceeded the chronic criteria during four storm events and the acute criteria during two. Oil and grease effluent EMCs for all storms sampled were near the MDL. However, oil and grease data were limited and may not have been well represented by first flush grab samples. Figures 28 and 29 show the influent and effluent EMCs for copper and zinc. Figure 30 shows the influent and effluent first flush oil and grease concentrations.

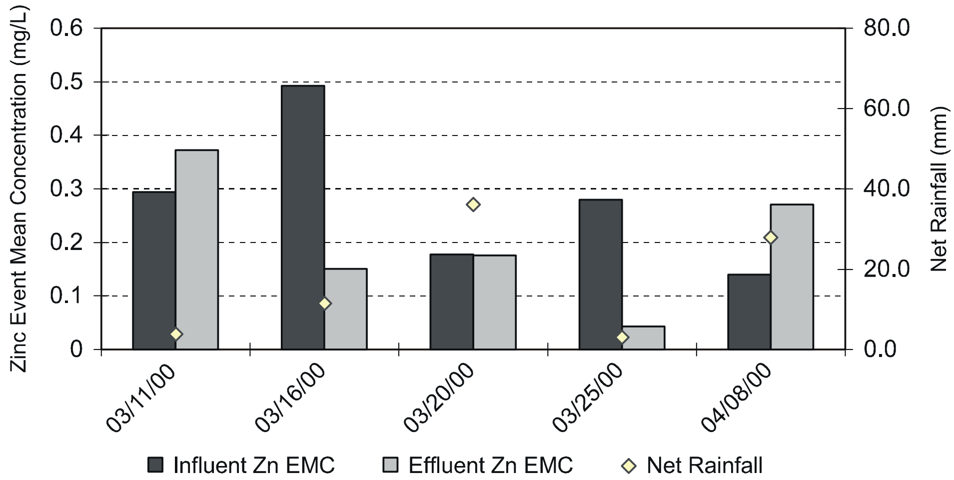

Figure 28. Vortechs: Event Mean Concentrations of Copper

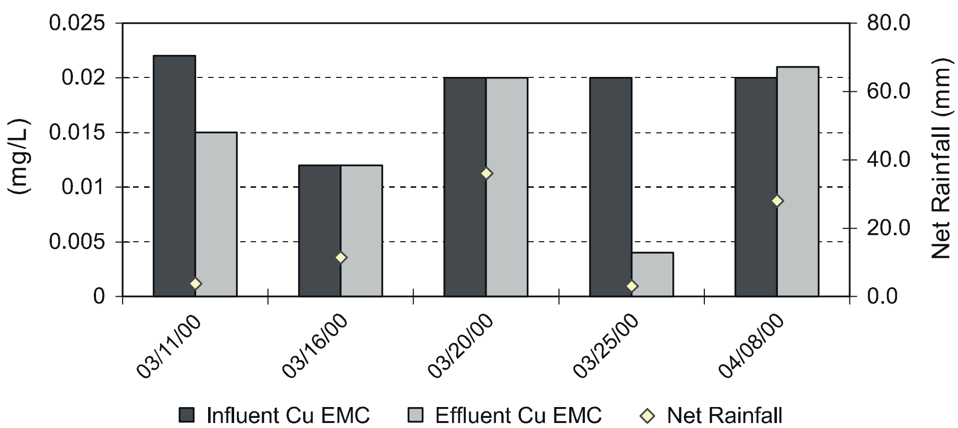

Figure 29. Vortechs: Event Mean Concentrtations for Zinc

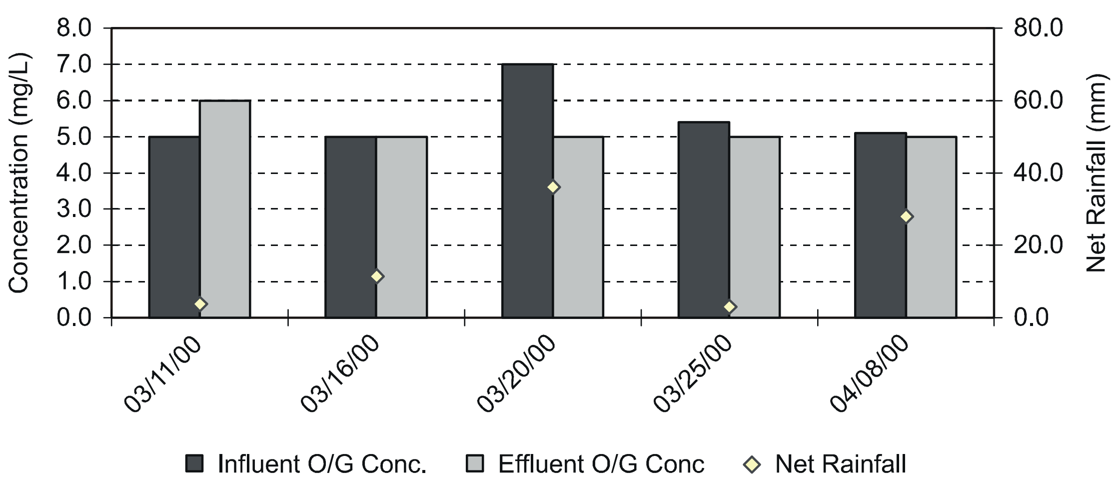

Figure 30. Vortechs: First Flush Oil and Grease Concentrations

Sediment Monitoring

Sediment Analysis

Sediment samples were taken when a sufficient amount of sediment had accumulated in the unit during the project. The Isoilater sediment sample was collected approximately 1 year after the last cleaning on 9/9/99. It is uncertain whether all the sediment had been removed during the cleaning. Therefore, the sediment data may reflect pollutant accumulation for more than a 1-year period. The Stormceptor was installed in February 1999. It is believed that the unit was not maintained from the time of installment because of the ongoing construction at the site. Therefore, the pollutant accumulation is for approximately a 1-year period. The Stormceptor sediment sample was taken on 1/24/00.

A composite scan for priority pollutants such as organics and metals was performed on the sediment extracted from the Isoilater and Stormceptor. The Vortechs did not accumulate a measurable amount of sediment during the time of monitoring, so no sediment sample was extracted for analysis. No semivolatile or volatile organics were detected in the Isoilater sediment. Two semi-volatile organic compounds were detected in the Stormceptor sediment sample: chloroform (<5.9 µg/kg; MDL = l.3µg/kg) and dichloromethane (<2.6 µg/kg; MDL = 1.3µg/kg).

Table 5. Metals Detected in Sediment Composite Scan

Metal[a] (mg/kg)	MDL (mg/kg)	Isoilater	Stormceptor	Gas[b] Station	Non-gas[b] Station	Hazardous Waste Regulatory Level[c] (mg/L)
Antimony	5.0	17.5	30	5.1	ND	NR
Arsenic	0.500	1.8	3.20	4.1	2.6	5.0
Barium	0.01	NA	0.01	NA	NA	100.0
Beryllium	0.500	ND	NA	0.3	0.5	NR
Cadmium	0.25	0.368	ND	6.5	0.8	1.0
Chromium	2.50	17.0	13.9	123	37	5.0
Copper	1.000	53.5	28.1	126	36	NR
Lead	5.0	5.7	11.4	493	46	5.0
Mercury	0.1000	0.15	0.1000	NA	NA	0.20
Nickel	2.00	8.70	8.35	50	50	NR
Silver	0.500	1.20	ND	ND	ND	5.0
Zinc	0.250	625	70	953	261	NR

NA = not analyzed; ND = not detected; NR = not regulated as hazardous waste.
[a]Total concentrations.
[b]Source: Schueler & Shepp (1995).
[c]EPA 40 C.F.R., Ch. 1 (7-1-99 edition).

The metal concentrations for the Stormceptor and Isoilater were closer to the range of concentrations found in Schueler's and Shepp's (1995) composite scan for non-gas station sites than that for gas station sites. However, copper and zinc in the Isoilater were present in considerably larger concentrations than found in non-gas station sites, and antimony was found at a much higher concentration than at gas station sites. The amounts of copper and zinc were much smaller when compared with those for gas station sites. The Stormceptor results were similar and showed a much smaller concentration of metals than non-gas station sites with the exception of antimony.

The sediment composite scan does reflect site-specific characteristics of runoff. Highway runoff would typically have higher zinc concentrations because of the leaching from road salt and automobile tires. Copper is found in coolant, brake fluid, motor oil, and gasoline. Spillage of these products can transport copper to receiving waters. In contrast, higher concentrations of antimony and lead were found in the Stormceptor than in the Isoilater. Antimony leaches from paint, rubber waste articles, household and industrial waste, and erosion from rocks and soils. Lead and copper have similar pathways, but lead is also leached from paints, stains, and plastics. Alkyl chlorides such as chloroform and dichloromethane are of industrial importance as solvents, paint removers, and degreasing agents. The pollutants found in the Stormceptor sediment sample corresponded well with expected pollutants found at construction sites. In addition, the zinc accumulation in the sediment was consistent with high zinc removal efficiencies. The zinc accumulation was greater than that of copper, which could be expected because copper is more soluble and zinc has a tendency to bind more to the soil. For the Stormceptor, copper individual storm load removal efficiencies were very low when compared with those for zinc.

Stormwater sediment toxicity varies and is site specific. BMPs in ultra-urban areas, especially hot spots, would be expected to have increased sediment toxicity. Sediment concentrations of chromium and lead exceeded the maximum allowable concentration of contaminants for toxicity as mandated by the EPA (40 C.F.R., Ch. 1 [7-1-99 edition]). Therefore, the sediment would require proper hazardous waste handling and disposal, which is costly.

Sediment Accumulation

Figure 31 shows the extraction of the Isoilater sediment on 3/31/00. The vertical height of the sediment column was 12.7 cm. When the coretaker samples were extracted, there was usually a cloudy layer of water just above the compacted sediment or sludge that is visible in the figure. Only the actual sediment or sludge was reflected in the reading. Reference points were selected for sediment depth measurements at the outflow riser pipe for the Stormceptor and Isoilater. The Vortechs unit had two reference points: the center of the grit chamber and near the influent pipe.

The Isoilater sediment depth was measured from May 1999 through April 2000. Frequent measurements were made during the time of storm sampling, and less frequent measurements (monthly basis) were made after the storm sampling was completed. Figure 32 shows a plot of the sediment accumulation in the Isoilater for almost 1 year. Initially, the sediment was very low (2.5 cm). Maintenance records showed that the unit was not cleaned prior to the first sediment depth measurement on 5/17/99. The Isoilater unit is regularly scheduled for cleaning in the late summer. Therefore, most of the sediment may have been washed out prior to the first reading during earlier months.

The sediment accumulation graph shows that the sediment depth changed both positively and negatively, indicating accumulation and resuspension. The cumulative net rainfall between sediment readings is also graphed with each data point. When the net rainfall increased above

Figure 31. Isoilater: Sediment Depth Measurement by Use of the Coretaker on 3/31/00

25.4 mm, the sediment depth decreased more often than it increased. The measurements taken on 9/7/99, 1/25/00, and 3/3/00 indicated a significant sediment decrease of 10.8 cm, 5.5 cm, and 21.8 cm, respectively; the corresponding net rainfall was 31.8 mm, 86.9 mm, and 87.6 mm. Sediment measurements were taken before and after a predicted hurricane storm that occurred before 9/7/00. The unit lost about 10.8 cm of sediment. The net precipitation prior to the last reading was the greatest during the monitoring period, and it produced the greatest sediment decrease of 21.8 cm.

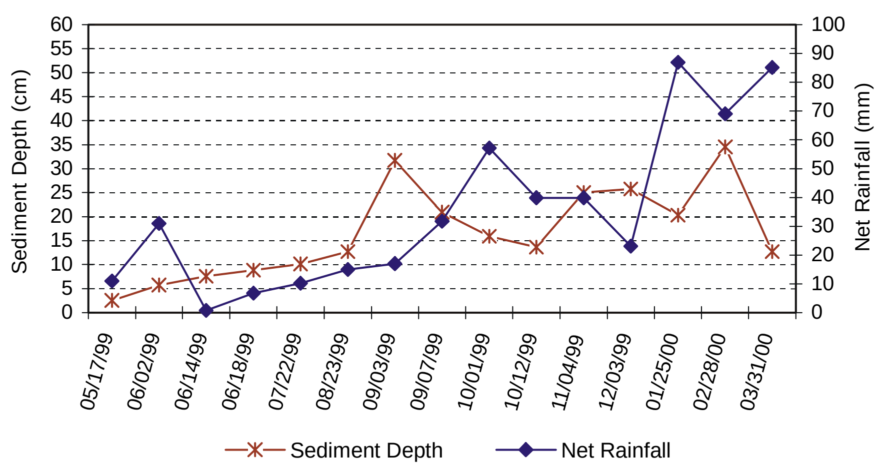

Figure 32. Isoilater: Sediment Accumulation (May 1999 through April 2000)

As scheduled, the Isoilater was cleaned on 9/13/99. During the cleaning, only the liquid fraction contents of the unit were removed. The cleaning did not remove any sediment. However, it was possible that a small sludge layer may have been resuspended and removed. A sediment measure on 10/1/99 showed a 5.0-cm decrease, which can also be attributed to a 57.2-mm net rainfall prior to the measurement. A maximum sediment depth of 43.2 cm is recommended by the manufacturer before cleaning is necessary. The maximum sediment depth observed during the monitoring period was 345.4 cm.

Sediment depth readings were also recorded for the Stormceptor and Vortechs. Figure 33 shows a graph of the sediment accumulation in the Stormceptor. The unit shows a consistent sediment accumulation, with the exception of a 10.16-cm decrease measured on 3/31/00. The unit was cleaned on 1/24/00. The manufacturer recommends maintenance for this unit when the sediment reaches 38.1 cm.

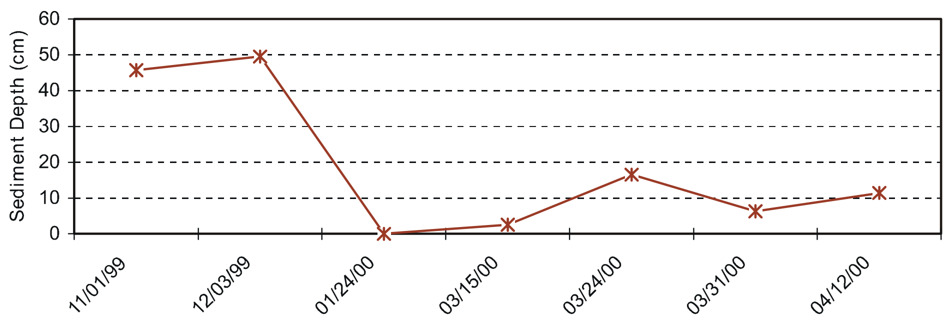

Figure 33. Stormceptor: Sediment Accumulation (November 1999 through April 2000)

With many of the sediment depth measurements, the Vortechs contained a layer of cloudy water when a coretaker sample was extracted, but no sludge or sediment was observed with many of the readings (Table 6). Initially, the unit had a sludge pile in the center (24.1 cm) and near the effluent pipe (9.9 cm), but later readings showed a decrease. In addition, during later readings, sediment could be "felt" by the coretaker, but not enough to be extracted (less than 2.5 cm). Therefore, the sediment depth could not be measured. Since the sediment in the Vortechs has the tendency to shift around and is resuspended during storms, locating the sediment may have been difficult. However, once the initial reference readings were taken, several tries were made with the coretaker to locate sediment. Again, no measurable amount was found. Since the unit was forced to function like a detention tank without a swirling motion, sediment accumulation would be expected to be poor.

Table 6. Vortechs Sediment Depth (cm)

Date	Influent Pipe	Center
2/28/00	17.5	29.2
3/15/00	7.6	5.1
3/24/00	NM	NM
3/31/00	NM	NM
4/12/00	NM	NM

NM = not measurable; very close to zero.

Site runoff characteristics could have affected the retention of sediments in the oil and grit separators. The Stormceptor sediment had a high fraction of clay at the reference measuring point, and all of the sediment residuals were entirely clay during clean out. In comparison, the Isoilater sediment was primarily sludge and silt near the reference measuring point and also during the time when the sediment sample was extracted for chemical analysis. These characteristics of the runoff can also affect the resuspension of sediment in the unit. Finer particulates are more easily resuspended and have a longer settling velocity.

Since the Isoilater and Stormceptor are similar in design and function, site conditions can be compared to some extent. However, the limited number of sediment depth measurements for the Stormceptor and Vortechs did not allow the researchers to discern trends without further long-term monitoring. The Isoilater monitoring data indicated that resuspension was frequent when rainfall depths exceeded 25.4 mm. Further, the sediment accumulation data may be extrapolated to reflect the sediment accumulation potential of BMPs similar in design and function such as the Stormceptor.

Comparison of Designs of Oil and Grit Separator Monitoring Sites

The PRE for each BMP is site specific and is dependent on many factors. Design factors and PREs are compared in Table 7 for the oil and grit separators in this study. The storage capacity of each BMP is the maximum wet-weather volume that the unit can hold while in operating mode. Since the Vortechs unit in this study had low influent flow rates, a dry-weather level estimation was assumed. In addition, the grit chamber was assumed to function like a detention tank similar to the Stormceptor and Isoilater. The Vortechs was not designed to function like a detention tank. Therefore, actual wet-weather sizing comparisons would be inadequate.

Table 7. Comparison of Designs of Oil and Grit Separators

BMPs	Isoilater (Warrenton)	Isoilater (Charlottesville)	Stormceptor	Vortechs[a,b]
Storage Capacity[c] (m^3)	7.57	3.79	14.20	1.67
Site Drainage Area (DA) (m^2)	809	809	10,117	2,428
Design Drainage Area[d] (m^2)	5,706	5,706	10,522	3,035
Column Height (cm)	305	107	396	91
Column Diameter (cm)	183	183	244	152
Storage Capacity/Site DA (m^3/m^2)	0.0094	0.0047	0.0014	0.00069
Storage Capacity/Design DA (m^3/m^2)	0.0013	0.00066	0.0013	0.00055
Oversize Factor (Design DA/Site DA)	7.05	7.05	1.04	1.25
Column Height/Column Diameter	1.67	1.58s	1.63	0.60
TSS PRE (%)	72.69	73.86	57.23	26.49
Average TSS Individual Storm Load Removal Efficiency (%)	71.43	57.18	48.33	17.43
Design TSS Removal Efficiency (%)	73.31	66.16	80.00	80.00
Average Influent TSS EMC	167.92	79.67	147.81	125.35

[a]Based on the length-by-width dimensions of the unit and dry-weather level height. The Vortechs unit influent pipe was approximately 30% full during monitoring. Therefore, high flows that would raise the water level in the unit above the dry-weather level were not typical for this unit at this specific site.
[b]Design drainage area is based on a 25-yr storm.
[c]Storage capacity is assumed for wet-weather conditions.
[d]Based on maximum treatable acreage.

The difference between the storage/site drainage area ratio and the storage/design drainage area ratio is the estimated excess storage capacity of the unit based on the design specifications. Typically, when units are oversized, the pollutant removal efficiency as well as the overall performance of the unit should increase because of the increased detention time.

Figures 34 and 35 show this trend to be consistent for the storms sampled during the monitoring period. Data for large storms (greater than 25.4 mm) were very limited. The Warrenton Isoilater unit has a significant oversized ratio and had a high TSS PRE primarily based on small-to-medium storms that was approximately equal to the expected design removal efficiency. The Charlottesville Isoilater unit has a similar oversize factor and had a high TSS PRE for the storm events sampled. Only 2 of the 12 storms included in the PRE calculations were over 25.4 mm. Both Isoilaters are oversized if compared to the maximum treatable drainage area and site drainage area, but the Charlottesville Isoilater has a significantly smaller storage capacity than the one at Warrenton. The Charlottesville Isoilater can treat high flows, but it is probably not effective for large storms when storage capacity is limited because of the detention time necessary for particles to settle. The Stormceptor and Vortechs units have a much smaller oversize factor, and the TSS PREs for both were much less when compared with those for the significantly oversized BMPs.

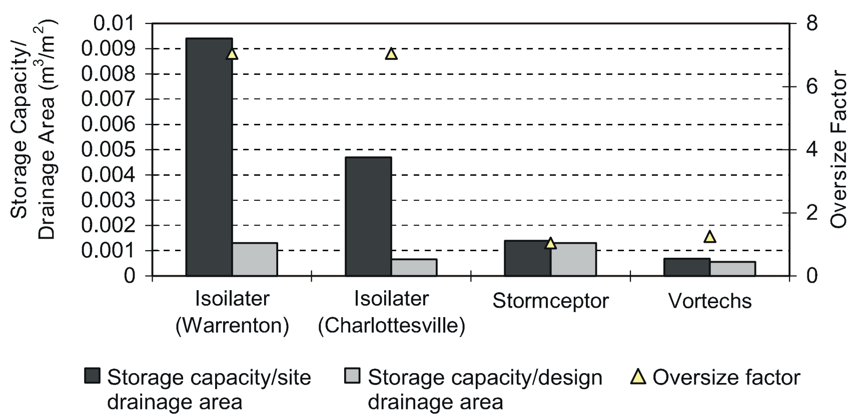

Figure 34. Oil and Grit Separators: Comparison of Design Parameters

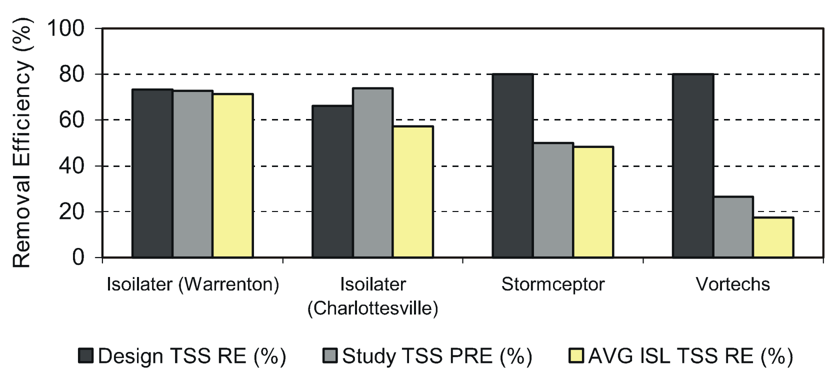

Figure 35. Oil and Grit Separators: Comparison of Period Removal Efficiencies for Total Suspended Solids

When units were oversized significantly, such as the Warrenton and Charlottesville Isoilaters, the TSS PRE was approximately equal to the average TSS individual storm load removal efficiency and the unit performed closer to the design TSS removal efficiency. Variations between individual storm removal efficiencies would be expected to decrease when oversize capacity increases. Although the number of PRE calculations for large storm events was limited, units with an oversize factor of 7 performed better than units with an oversize factor of 1. Units with an oversize factor of 7 had TSS PREs comparable to the design TSS removal efficiency. However, units with an oversize factor of 1 had TSS PREs below the expected design TSS removal efficiency.

The storage capacity of the BMPs can also contribute to the removal efficiency per storm event (with the individual storm load method). Both the Warrenton and Charlottesville Isoilaters had good average TSS individual storm load removal efficiencies, regardless of storm size. During the two monitoring periods for the Warrenton Isoilater, no bypass storms were sampled and no storms were associated with negative TSS removal efficiencies. However, only three large storms (greater than 25.4 mm) were sampled, and of the three, only one storm was sampled completely. Further monitoring is needed to access the impact of larger storms on pollutant removal efficiency. Medium-to-small storms did not seem to affect the efficiency because the drainage area was small compared to storage capacity. Bypass would occur less frequently or not at all.

The storage capacity of the Stormceptor is close to the design drainage area, so the influent flow rate entering the BMP was expected to be high. The system does undergo bypass, as evident from the monitoring data (the storm on 3/20/00). When bypass occurs in vault/reservoir BMPs with a disk insert and a bypass weir system, sediment residuals from the runoff are left behind on the platform. This was the case for two Stormceptor units and another Isoilater unit in the Charlottesville area.

Cost Comparison of BMPs

The economics associated with implementing ultra-urban BMPs are of significant importance to water quality managers and to the long-term longevity of the BMPs themselves. A cost analysis was performed using the actual costs associated with the BMPs monitored in this study (Table 8). Unit costs for each oil and grit separator BMP varied depending on model size. Some of the high installation cost of the Vortechs unit was due to the unit being retrofitted in an area of steep grade with extreme land constraints. Sufficient data were not available for a cost/benefit comparison of prices of other proprietary BMPs. The EPA (1999c) cited a price of \$60,000 per bioretention area for a 20,234-m^2 commercial site with 65% impervious cover, which translates to approximately \$12,000/4046.9 m^2 served. The costs for the bioretention area monitored in this study were slightly higher, which can be attributed to the fact that BMPs have economies of scale and costs are variable depending on region and site constraints.

Table 8. Costs (in Dollars) Associated with Different Management Options[a]

BMP	Unit Cost	Installation Cost	Maintenance Cost	Cost/ m^2 Served	Cost/m^2/ Yr[b]	% TSS Reduction During Study	Cost/ % TSS Reduction
Isoilater	10,200[c]	7,000	1,780	3.01	0.37	73	0.0051
Bioretention area	15,000-20,000[d]	Included in unit costs	Landscaping (300/yr)	4.32	0.16	53	0.0030
Stormceptor	16,700	4,200-5,900[e]	3,500-5,000[e]	2.07	0.45	57	0.0028
Vortechs	14,000	17,580	2000[e]	10.40	0.87	26	0.033[f]

[a]Costs do not reflect any discounts. Unit costs do not include delivery and sales tax. Unless noted, actual costs are shown in the table of the BMPs monitored in this study.
[b]Capital costs amortized over 50 yr plus maintenance costs.
[c]Quoted from Americast (2000). This unit is no longer available.
[d]Construction costs. Quoted by independent licensed disposal contractors in the surrounding area.
[e]Installation costs are typically 25% to 35% of the unit cost.
[f]Improper installation affected cost/benefits.

Actual maintenance costs were significantly greater when compared with the approximated costs from the literature and the EPA. Typical maintenance costs in the literature were estimated to be approximately $1,000. Actual maintenance costs for the BMPs in this study were well over $1,000, with the exception of those for the bioretention area.

Cost per square meter served represents the total unit costs plus installation cost per design drainage area. Since the Warrenton Isoilater was significantly oversized, the costs were high. Further, the high installation costs for the Vortechs are also reflected in the cost per square meter served ratio. The maintenance costs for the Stormceptor were expected to be high because the unit has a large storage capacity and a large volume of residuals would need disposal when compared with a unit with a smaller storage capacity. When capital costs were amortized over 50 years and added to the maintenance costs to determine a cost per square meter per year, costs were high again for the Isoilater and Vortechs BMPs. A cost comparison was performed using the TSS PREs for the sites monitored. The potential long-term costs associated with the bioretention area were significantly less when compared with those associated with the proprietary oil and grit separators.

CONCLUSIONS

The results in the study are site specific since the performance of the BMPs was affected by varying factors. The study, thus, concludes that the data and study site conditions must be evaluated carefully before results can be extrapolated to compare the relative and potential performance of a particular BMP under different site conditions.

Nevertheless, the following specific conclusions may be useful.

Isoilater

- *The Isoilater has a high TSS removal efficiency and positive removal efficiencies for the other water quality constituents monitored in this study. Because of its increased storage capacity, the removal efficiency for an individual storm is increased.*

- *For small-to-medium storms, the Warrenton Isoilater is effective in providing water quality benefits.*

- *The Isoilater has a high potential for sediment resuspension when the rainfall depth exceeds 25.4 mm, which would typically be considered a large storm.* Therefore, the unit is ineffective in trapping pollutants contained within the sediment residuals that are deposited from a recent storm, events that can accumulate in excess of the hazardous waste regulatory concentration levels. Further monitoring of larger storms might support observations of the sediment resuspension.

Bioretention Area

- *For the bioretenion area, TSS removal efficiencies are affected by rainfall depth.* Small-to-medium storms are associated with positive removal efficiencies, and large storms are associated with negative removal efficiencies.

- *Because of the extended detention time of the bioretention area, 100% removal can be achieved for small storms that do not produce outflow.* The bioretention area has a detention time of approximately 6 h.

- *PREs for the bioretention area showed promise because they were primarily based on the early growing stages of the bioretention and they were conservative because influent and effluent mass loadings were not used to calculate removal.* Plant uptake removal would have been minimal during the monitoring study period. In addition, leaching from the bioretention area may have interfered with sampling results. To establish a forest community structure for optimal performance, the bioretention area requires an initial stabilization and growing period, which could take a few growing seasons.

Stormceptor

- *The Stormceptor is associated with positive PREs for all water quality constituents monitored except for TN.* The TSS PRE (57%) was below the design removal efficiency of 80%. Since the design guidelines are based on drainage area served, not site pollutant loading characteristics, the removal efficiency results can be expected to be below the design removal efficiency during construction.

- *No conclusions may be reached about sediment depth accumulation and resuspension in the Stormceptor. Further, chemical analysis of sediment residuals from the Stormceptor* *indicated that pollutants could accumulate in excess of the regulatory hazardous waste concentration levels.*

Vortechs

- *Since the Vortechs unit was improperly installed, no conclusions about its functionality may be reached.* However, a few observations were made. The removal efficiency results were underestimated and showed that the unit was providing treatment to some degree, which is critical because the effluent discharges directly to an impaired water body. The unit also provides spill containment capacity, which is also critical to this sensitive area. The cost analysis indicated that the unit was relatively expensive because of the high installation costs. The limited sediment data also showed that the Vortechs system in this study had poor sediment retention.

Cost Comparison

- *The bioretention area is the most cost-effective of the BMPs monitored in this study*. High installation and maintenance costs of proprietary BMPs increased long-term costs significantly. In addition, costs per design drainage area served also increased because of the need to oversize BMPs. With regard to the TSS PREs, the proprietary BMPs monitored in this study were very costly alternatives when compared with the bioretention area.

Sediment Analysis

- *Sediment residuals trapped in the Isoilater and Stormceptor had high metal concentrations, and some of these concentrations were in excess of the hazardous waste standard.* Therefore, maintenance costs would increase significantly and proper disposal would be required.

RECOMMENDATIONS

1. *To maximize pollutant removal efficiencies for BMPs to the optimal levels specified by the manufacturers, (1) install the BMP correctly in accordance with the installation requirements specified by the manufacturer; (2) regularly and properly maintain the BMP; and (3) match the size of the BMP with site conditions.*

2. *Measure sediment depth monthly during the first year of installation to determine how rapidly sediment is accumulating and if sediment is being resuspended. After the first year, measure the sediment depth for all oil and grit separators at least on a seasonal basis (four times a year) and after large storm events.*

3. *Clean out a BMP at least once a year, and alter this schedule based on sediment accumulation.* It may be more cost-effective to clean out units twice a year to prevent sediment residual concentrations from accumulating to hazardous concentrations. The

necessity for this can be determined based on the first initial cleanout, and a simple cost analysis can be performed to determine if cost savings exist.

4. *Since the maintenance costs for some ultra-urban BMPs are relatively high, obtain maintenance pricing estimates from local contractors and inquire about sediment residual waste disposal as part of the overall cost consideration.* Most contractors have a base labor charge that might offset any cost-saving benefits. These factors should be carefully evaluated to determine the most cost-effective approach to residual management.

5. *Document the sediment depth measurements and the cleanout information.* Use these data to help determine the overall efficiency and longevity of the BMP.

6. *Monitor ultra-urban BMPs, particularly oil and grit separators, that are installed in new development areas during construction for pollutant buildup.* Clean them out when sediment levels exceed the recommended sediment capacity necessitating maintenance. If there is another form of pollutant control active downstream of the BMP at the construction site that would provide water quality benefits, monitor the BMP for clogging. Clean out the BMP and fill it to capacity with water after construction has ceased. Pay careful attention to determining the expected water quality benefits of oil and grit separators during construction and their incorporation in the overall pollution prevention plan.

7. *When conditions such as volume reduction requirement, space availability, etc., are favorable, consider implementing a bioretention area, which appears to be a cost-effective BMP.*

8. *Be careful when sizing units for sites with extremely high pollutant loadings because a decrease in storage capacity will impede performance.* Sizing criteria for high loading areas can be extrapolated to some degree from the Stormceptor monitoring site in this study.

9. *Adjust improperly installed BMPs to improve their function as specified by the manufacturer.*

10. *With regard to the BMPs monitored during this study, take the following actions:*

    - Realign the influent pipe of the Vortechs to improve the BMP’s performance and increase water quality benefits to the receiving water body.

    - Provide immediate maintenance for the bioretention area to ensure its function and longevity. Thereafter, perform annual inspections and maintenance. Evaluate the bioretention area further when it has matured and stabilized.

    - During future sampling, use weirs to measure flow when depth sensors are unreliable at low depth flows. Influent strainers should be placed far enough upstream to ensure they will not be affected by the interference caused by the weirs. Calibration curves should be calculated when possible to verify sampling points. Future monitoring of the oil and grit separators should include sediment accumulation monitoring, and storm event sampling criteria should be evaluated carefully for monitoring studies.

SUGGESTIONS FOR FURTHER STUDIES

This study demonstrates the potential benefits of using ultra-urban BMPs for treating stormwater runoff. Since data on the field performance of ultra-urban BMPs are very limited and highway construction sites typically have limited space available for BMPs, further studies would be beneficial to VDOT in establishing maintenance programs. Suggestions include:

- Continue monitoring the Stormceptor unit once construction has ceased and the drainage area has been stabilized. This would allow a determination of its performance after runoff loading characteristics have changed to expected long-term loadings.

- Monitor another fully mature and stabilized bioretention area.

- Continue monitoring the Vortechs unit after the influent pipe has been properly aligned.

- In order to determine precisely the rate of sediment accumulation in oil and grit separators, continue long-term monitoring of the sediment depth of the various oil and grit separators on the UVA grounds as well as other oil and grit separators in the proximity of UVA.

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