Storm-Water Bioretention for Runoff Quality and Quantity Mitigation

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Abstract: In response to water quality and quantity issues within the Stroubles Creek watershed in Blacksburg, Virginia, a retrofit bioretention cell (BRC) was installed to collect and treat runoff from an existing parking lot. The BRC was completed in July 2007, and 28 precipitation events were monitored between October 2007 and June 2008. For each storm, inflow and outflow flow-weighted composite samples were collected and analyzed for suspended sediment, total nitrogen, and total phosphorus. The inflow and outflow concentrations and loads, as well as total inflow and outflow volumes and peak flow rates, were analyzed to evaluate BRC efficiency. Overall, the BRC successfully reduced flow volumes and peak flow rates leaving the parking lot by 97 and 99%, respectively. Cumulative mass reductions for sediment, total nitrogen, and total phosphorus all exceeded 99% by mass. The findings of this study have significant implications for areas with karst geology: (1) current design recommendations of lining the bottom of BRCs with clay may not be sufficient to prevent large amounts of water from infiltrating into surrounding soils; and (2) in areas with significant elevation changes, designing BRCs deeper than the typical 0.6–1.2 m increases the feasibility of retrofits and provides substantial water quality and quantity benefits. **DOI: 10.1061/(ASCE)EE.1943-7870.0000388.** *© 2011 American Society of Civil Engineers.*

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Introduction

The conversion of forested and agricultural land to urban land is one of the most prevalent forms of land alteration in the United States, and many facets of urbanization make it a threat to water quality (Schoonover and Lockaby 2006). Increases in impervious surfaces and soil compaction reduce infiltration rates, thereby decreasing groundwater recharge, increasing the frequency and magnitude of high flows, and increasing flow variability (Meyer 2005). Increases in runoff and the significant amount of land disturbance required by construction greatly increase the amount of sediment introduced to surface water bodies via erosion and channel incision (Colosimo and Wilcock 2007). Numerous studies have demonstrated elevated concentrations of nutrients, such as nitrogen and phosphorus, as well as other substances, including chlorine, sulfate, and ammonium in urban streams (Biggs et al. 2004).

Bioretention cells, also called rain gardens, are composed of a porous media, mulch, and vegetation. Water collects in the bioretention cell and infiltrates into the media, which is usually composed primarily of sand. Soil fines and leaf compost can be added to the sand to manipulate the media infiltration rate and organic matter content. The media is covered with a layer of mulch, and the area is planted with pollution- and water-tolerant trees, shrubs, and herbaceous species (Davis et al. 2001). The primary goals of bioretention are to decrease surface runoff, increase groundwater recharge, and remove pollutants from storm water entering the facility (Dietz 2007). Previous studies demonstrate that bioretention effectively removes sediment and nutrients from stormwater (Davis et al. 2001; Glass and Bissouma 2005; Dietz and Clausen 2005; Hsieh and Davis 2005; Hunt et al. 2006; Weiss et al. 2007). In addition, a 1-year study in Haddam, Connecticut, conducted by Dietz and Clausen (2005) reported that 98.8% of the water that entered a bioretention cell was treated and exited the system via underdrains, indicating substantial treatment of inflow by a bioretention system.

Bioretention is a primary component of a new form of storm water management termed low impact development (LID) (Dietz 2007). The overall goal of this approach is to "mimic the predevelopment site hydrology by using site-design techniques that store, infiltrate, evaporate, and detain runoff" (Prince George's County 1999). LID has slowly gained acceptance as a new storm water management method. Some municipalities have instituted regulations that require the implementation of LID practices in new developments, including bioretention; others use financial incentives to promote this new form of storm water treatment and control. The goals of this study were to assess the impact of retrofitting an existing parking lot with a bioretention cell with regard to peak flow rates and runoff volumes leaving the site, and to quantify total nitrogen, total phosphorus, and suspended sediment reductions caused by the best management practice (BMP). (The terms BRC and BMP will be used interchangeably throughout the remainder of this paper.)

Methods and Materials

Site Description

The study site, located at 37°14' N, 80°24' W in Blacksburg, Virginia (Fig. 1), is situated in the Ridge and Valley physiographic

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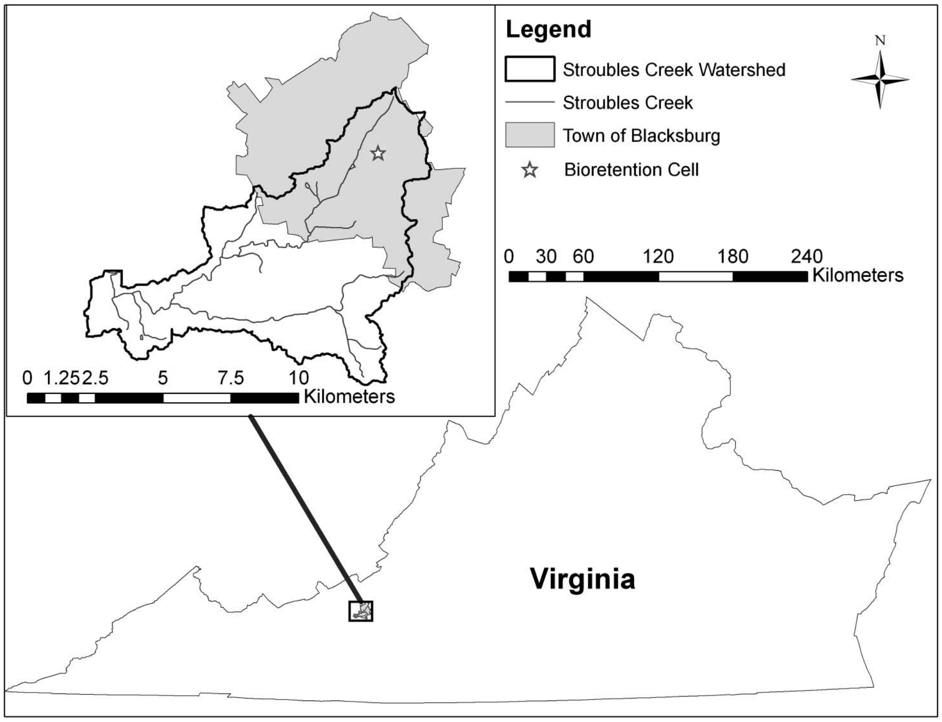

Fig. 1. Location of the studied bioretention cell in relation to the state of Virginia, the Town of Blacksburg, and the Stroubles Creek watershed

province, between the Alleghany and Blue Ridge Mountains. On average, the site receives approximately 109 cm of rainfall per year and experiences mean daily maximum temperatures of 5 to 28°C [National Climate Data Center (NCDC) 2008].

A retrofit bioretention cell (BRC) was constructed at the Blacksburg Aquatic Center to treat runoff from the existing parking lot and to serve as a research and demonstration project. The Aquatic Center is located approximately 2.7 km from Blacksburg and is a year-round indoor aquatic facility that serves local residents throughout the year. Existing storm water management at the site consisted of traditional curb and gutter and dry detention ponds, which discharged runoff to an unnamed tributary of Stroubles Creek. The watershed draining to the BMP included a 0.16-ha impervious parking lot and approximately 65 m^2 of turfgrass surrounding the BMP.

BMP Design

The design of the retrofit bioretention cell was based on requirements and recommendations set forth in the Virginia Stormwater Management Handbook [Virginia Department of Conservation and Recreation (VADCR) 1999]. These requirements state that the BMP must be sized to hold the first 13 mm of runoff from the watershed and to match the predevelopment peak flow rates of a 2-year and a 10-year, 24-h storm event. To determine the BMP size necessary to meet these requirements, a comprehensive hydrologic budget model was developed using STELLA, a modeling program with an icon-based graphical interface (ISEE Systems, Inc., Lebanon, New Hampshire). The main components of the model were runoff entering the BMP (Natural Resources Conservation Service curve number method); evapotranspiration from the BMP (Thornthwaite method); percolation of water through the BMP media (Horton's equation); exfiltration into the subsoil (Horton's equation); outflow from the BMP; and overflow from excess ponding.

Spatial and infrastructure constraints limited the available area for the BMP; therefore, the treatment volume within the BRC, as determined by the hydrologic model, was achieved by making the cell deeper than the typical 0.6–1.2 m. The dimensions of the BRC were 4.6 m long, 7.6 m wide, and 1.8 m deep, resulting in a BMP surface area to drainage area ratio of approximately 2.1%. This is lower than the standard design ratios of 5–7% discussed by Hunt et al. (2006), as well as the recommended minimum of 2.5% in the Virginia Stormwater Management Handbook (VADCR 1999); however, this was a retrofit BMP and, in most cases, site constraints limit the extent to which retrofit practices can conform to standard design methods.

As recommended by Hunt and Lord (2006), the BRC was filled with a mixture of 88% washed medium sand, 8% clay and silt fines, and 4% leaf compost, which were not compacted and were overfilled to allow settling. The drainage layer, located 30 cm above the bottom of the BMP, consisted of two sets of two (a total of four) parallel, 10-cm-diameter perforated pipes, covered with #57 stone and wrapped in filter fabric to prevent clogging by fines. These underdrains connected to an outflow structure, which discharged to an existing dry detention pond. The 30-cm ponding depth at the bottom of the BRC was designed to create an internal water storage (IWS) zone, which was included to promote denitrification between storm events. Because of underlying karst geology, significantly increasing infiltration in an isolated area was not recommended; therefore, a 15-cm compacted clay layer was installed on the bottom of the cell to prevent water from infiltrating into the subsoil. The bottom and sides of the BMP were lined with a permeable filter fabric to prevent the surrounding soil from intruding into the cell and clogging the media. The media was covered with 10 cm of hardwood mulch to encourage plant growth, and a variety of hardy native perennials, shrubs, and trees were planted to maintain infiltration rates and promote pollutant removal. Water ponded on the BRC surface in excess of 10 cm overflowed into the outlet structure, which discharged to the dry detention pond.

Monitoring

Independent runoff events were defined as storms having a minimum of 6 h between inflow events; otherwise, all samples were considered representative of a single event. A tipping-bucket rain gauge, located approximately 0.4 km from the study site, measured precipitation depth and intensity. Because of equipment malfunction, rainfall data were not recorded at this location from February 7, 2008, to March 28, 2008. Precipitation data during this time period were obtained at a nearby weather station operated by the U.S. National Oceanic and Atmospheric Administration and located at the Virginia Tech Airport, approximately 5.5 km from the study site. This station records precipitation data every 20 min.

Thel-Mar compound v-notch/rectangular weirs and bubble levelers (Thel-Mar, Brevard, North Carolina) were installed in the BMP inflow and outflow pipes. ISCO 6700 samplers (0.3-mm accuracy; Teledyne Isco, Inc., Lincoln, Nebraska) with bubbler-level flow modules recorded water levels every minute. The ISCO samplers were programmed to begin sampling when water flowed over the weir crest and to take a discrete sample of approximately 1 L following every 2.8 m^{-3} of runoff. Flows less than 1.2E-5 L/s were not recorded.

Two sets of two nested piezometers were installed in the BRC to observe water movement through the system. Each set included a piezometer that extended to the bottom of the BMP and one that extended to 0.9 m above the bottom of the BMP. The piezometers were constructed of five-cm diameter PVC pipe with an end cap. Holes 0.64 cm in diameter, at an approximate spacing of 1.9 cm, were drilled to a height of 10 cm above the end cap. Unvented Onset HOBO Model U20 pressure transducers (0.3-cm accuracy; Onset Computer Corp., Bourne, Massachusetts) recorded total pressure at 1-min intervals. Barometric pressure data were recorded at the Heth Farm (4.8 km from the site) at 5-min intervals by a Vaisala PTB101B analog barometer (0.015 kPa accuracy; Vaisala Oyj, Vantaa, Finland) and were used to correct the piezometer data to determine water level within the BMP.

Laboratory Analyses

Samples taken within an individual storm event were composited to produce a single influent and a single effluent flow-weighted sample for each runoff event. Each composite sample was analyzed for total nitrogen (TN), total phosphorus (TP), and suspended sediment concentration (SSC). TN and TP concentrations were analyzed using Hach methods 10071 and 8190, respectively (Hach 2002), and suspended sediment concentrations were determined using ASTM Method D 3977-97. Method detection limits for TN, TP, and SSC analyses were 0.5 mg/L, 0.02 mg/L, and 1 mg/L, respectively. Storm water runoff samples were stored in acid-washed plastic bottles at 4°C prior to laboratory analysis. Samples were analyzed within the holding times recommended by the U.S. EPA (2002). One duplicate was run for every 20 samples for each test performed, and one sample spiked with a known concentration (quality control standard—QCD) was run for every set of samples. Acceptable ranges for the values of duplicates and QCDs for each of the individual tests were determined as stated in the Technology Acceptance Reciprocity Partnership (TARP) (2003). If the duplicates and/or QCDs did not fall within the specified range, the test was repeated for the entire set of samples until the values were in compliance. Samples that resulted in an "under range" reading were recorded as half the lowest detectable value for the testing method.

Samples of the sand, topsoil, and leaf compost were collected as they were mixed to create the bioretention media. A composite sample of potting soil was created by taking subsamples of the planting medium from several of the plants placed in the BMP, and mulch samples were collected as it was spread. Each of the media components was tested for total nitrogen, total phosphorus, and Mehlich-III phosphorus using methods published by the American Society of Agronomy and Soil Science Society of America [SW 846-6010B for TP, MSA Part 2 (1996); Dumas Method for TN] (Page 1982). Samples that were not homogenous, such as the mulch, were ground to create a mixture representative of the overall sample before being analyzed.

Data Analyses

Precipitation data collected by the tipping-bucket rain gauge were used to determine storm length, average and maximum rainfall intensity, duration of preceding dry weather, and total precipitation for each storm event. Pressure data recorded by the HOBO pressure transducers were corrected using the continuous barometric pressure record and converted to centimeters of water. Water-level (head) data, monitored via the bubbler levels and flow modules, were used to calculate flow rates and total volumes for each storm event using a rating curve developed from the manufacturer-provided weir rating table.

Total mass loads for each storm were determined by multiplying the concentration of the flow-weighted composite sample by the total volume. Percent removal calculations were performed using total mass loads. The findings and conclusions reported subsequently refer to total mass loads, not concentrations, unless otherwise noted. Finally, peak flow rates were identified for individual storm events as the largest flow rate recorded during the entire event.

Statistical Analyses

The total outflow mass load for TN, TP, and SSC for each storm was subtracted from the total inflow mass load to determine the change in runoff pollutant mass attributable to the BRC. Similarly, the total outflow volume was subtracted from the total inflow volume. The data were checked for normality using the Shapiro-Wilks test (Dalgaard 2002). Nonnormal data were analyzed using a paired, one-sided, nonparametric Wilcoxon Signed Rank Test to test for significant changes in TN, TP, and SSC mass loads, as well as runoff volume and peak flow rate through the BMP. Normally distributed data (peak flow rates and TN, TP, and SSC concentrations) were analyzed using a one-sided, paired *t*-test. The nonparametric Spearman's ρ correlation test was used to investigate correlations between precipitation, flow, volume, and pollutant removal rates (Dalgaard 2002).

An alpha-value of 0.05 was used for all statistical tests to determine significant differences. All statistical analyses were performed using the statistical software *R*, version 2.6.2 (Dalgaard 2002).

Results and Discussion

Precipitation

Monitoring of the BRC began on November 9, 2007, and was discontinued June 1, 2008. During this time period, a total of 41 precipitation events occurred, with 28 of these storms producing inflow into the BMP. An average of 0.8 cm of rainfall fell per storm, with an average intensity of 0.7 cm/h. Total rainfall depth and duration data for each storm are shown in Fig. 2.

When compared with the 30-year monthly averages from years 1971–2000 (NCDC 2008), the rainfall amounts received during the study period were much lower. This lack of rainfall was

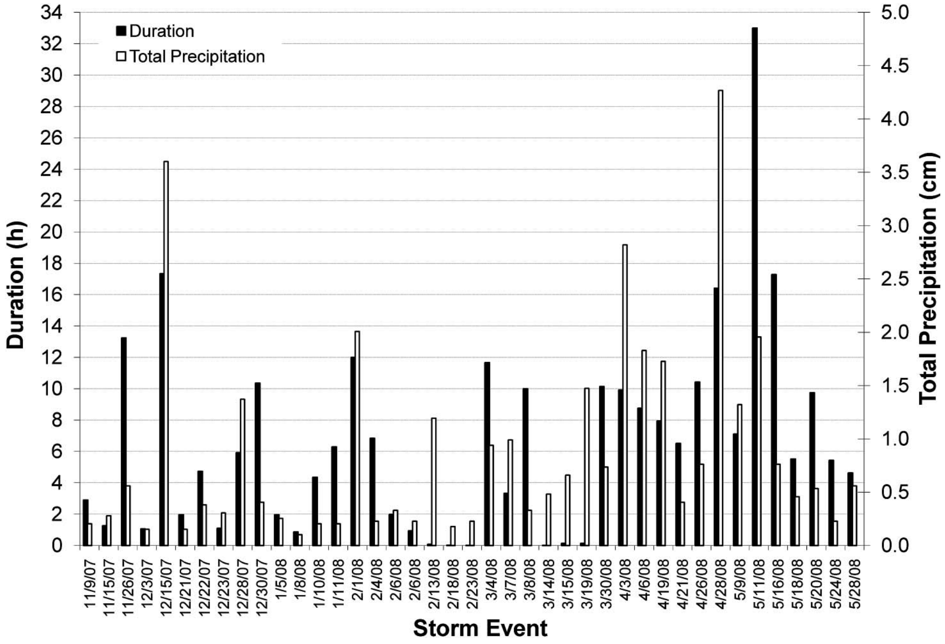

Fig. 2. Storm duration and total precipitation of monitored storm events for the study site in Blacksburg, Virginia

representative of the weather patterns experienced during 2007, as many parts of the United States, the study site included, suffered a severe drought. A report issued by the Virginia Department of Environmental Quality on October 22, 2007, stated that "exceptional drought conditions [persisted] in southwest Virginia" and rainfall amounts received during the preceding year were well below normal [Virginia Department of Environmental Quality (VADEQ) 2007]. A status report issued on March 25, 2008, stated precipitation deficits had not improved since October, but the severity of the drought throughout Virginia was slightly reduced (VADEQ 2008). As the results of this study are not representative of normal rainfall patterns, it is possible that the BRC performance would differ during periods of larger, more frequent precipitation events.

Flow Volumes

Of the 28 monitored precipitation events that produced inflow to the BRC, only five produced outflow. Table 1 displays flow and concentration data for all storm events that produced inflow to the BMP. The majority of water that entered the BMP was treated by infiltrating through the BRC media; on the basis of 1% was left as untreated surface overflow.

The only monitored precipitation event that produced overflow was storm 20. This storm was characteristic of a convective thunderstorm, producing large amounts of rainfall in a very short time period; he storm produced 1.5 cm in 0.13 h (11.3 cm/h), generating a maximum inflow rate of 12.6 L/s. The existing mulch layer and underlying sand were raked smooth and new mulch was applied on March 13, 2008. The storm occurred on March 19, 2008, and the high inflow velocities cut a path directly through the middle of the BMP to the overflow grate; little runoff infiltrated. The new mulch was loose and did little to slow down the inflow. Additionally, the plants in the BRC had not grown over the winter months and were not yet big enough to block the incoming water and create a longer flow path from the inflow pipe to the overflow grate. The BMP was designed with 15 cm of surface ponding; however, the media were not compacted during construction and had not yet settled to the design depth. This lack of ponding volume also contributed to the overflow occurrence. Water-level data recorded by the piezometers indicated there was no treated outflow produced during this storm event.

During the study period, a total of 108,461 L entered the BMP, whereas only 2,805 L exited the BMP, producing a cumulative volume reduction of 97%. The median volume reduction, when calculated on the basis of all individual storms, was 100%. When only the five storms that produced outflow were analyzed, the median volume reduction was 98%. Water that did not exit the BRC as outflow or overflow is hypothesized to have left the cell via exfiltration or evapotranspiration (ET) (although ET would be minimal during winter months).

Statistical analyses verified that the water volume entering the BMP was significantly greater than the volume leaving the BMP ($p = 1.86\text{E-}9$). As would be expected, statistical analyses also identified a negative correlation between inflow volume and percent reduction in flow volume ($\rho = -0.59$, $p = 0.0007$), indicating larger storms have a greater chance of producing outflow and, thus, have a lower percentage volume reduction.

During BMP construction, a bedrock outcropping was encountered in the northeast corner of the bioretention cell; the bedrock was drilled away, and construction continued as planned. As recommended by the Virginia Stormwater Management Handbook (VADCR 1999), the bottom of the cell was lined by compacting in situ clay to a depth of 15 cm; however, the vertical sides of the cell were lined with a permeable fabric. The soil surrounding the BMP was primarily fill dirt put in place when the Aquatic Center was constructed in 1992 and consisted mostly of clay. It is likely that water was rapidly lost through the sides of the BMP via cracks in the fill dirt and/or through cracks in the bedrock, thus causing significant reductions in outflow volumes. Considering the bedrock outcropping was located in the upstream end of the BMP and the area was suffering from a severe drought, cracks within the surrounding soil were the most likely conduit for the infiltrated runoff.

This was an important finding regarding the placement of retrofit BMPs in existing fill and karst geology: Even though surrounding soils were predominantly clay, the loss of water from the BMP was very high. Although this water could have been lost via

Table 1. Summary of Inflow and Outflow Data for Monitored Storm Events

Storm ID	Date	Flow (L)		Peak flow (L/s)		Suspended sediment (mg/L)		Total nitrogen (mg/L)		Total phosphorus (mg/L)	
		In	Out	In	Out	In	Out	In	Out	In	Out
1	11-26-07	468	0.0	0.025	—	166	—	3.4	—	0.25	—
2	12-03-07	24.7	0.0	0.003	—	170	—	3.8	—	0.38	—
3	12-21-07	512	0.0	0.004	—	26	—	1.8	—	0.17	—
4	12-23-07	1,730	0.0	0.054	—	96	—	1.4	—	0.25	—
5	12-28-07	9,780	468	0.064	0.006	44	33	0.25	0.25	0.14	0.18
6	12-30-07	1,420	0.0	0.060	—	28	—	1.1	—	0.14	—
7	01-08-08	87.2	0.0	0.006	—	195	—	2.5	—	0.41	—
8	01-10-08	154	0.0	0.005	—	106	—	1.4	—	0.28	—
9	01-11-08	800	0.0	0.623	—	59	—	1.6	—	0.20	—
10	02-01-08	5,550	22.8	1.160	0.009	224	9	7.2	5.8	0.32	0.13
11	02-04-08	234	0.0	0.440	—	293	—	3.3	—	0.88	—
12	02-06-08	859	0.0	1.160	—	217	—	6.4	—	4.96	—
13	02-06-08	1,630	0.0	2.770	—	546	—	3.3	—	4.76	—
14	02-13-08	2,540	0.0	1.840	—	593	—	5.1	—	0.70	—
15	02-18-08	319	0.0	0.198	—	98	—	3.2	—	0.40	—
16	02-23-08	132	0.0	0.275	—	260	—	2.1	—	0.60	—
17	03-07-08	546	0.0	0.226	—	82	—	1.4	—	0.97	—
18	03-14-08	3,580	0.0	2.430	—	32.7	—	3.0	—	1.63	—
19	03-15-08	996	0.0	0.538	—	1,223	—	1.3	—	1.03	—
20	03-19-08	5,240	0.8	12.6	0.011	393	872	0.7	5.3	1.04	2.30
21	04-03-08	15,200	0.0	6.13	—	—	—	—	—	—	—
22	04-06-08	6,870	1,500	3.44	0.721	—	—	—	—	—	—
23	04-26-08	41,700	816	22.4	2.090	—	—	—	—	—	—
24	04-28-08	187	0.0	0.510	—	—	—	—	—	—	—
25	05-09-08	6,850	0.0	8.580	—	—	—	—	—	—	—
26	05-20-08	850	0.0	0.510	—	77.0	—	0.9	—	0.83	—
27	05-24-08	49.2	0.0	0.120	—	54.8	—	1.7	—	1.20	—
28	05-28-08	85.8	0.0	0.120	—	25.8	—	2.4	—	0.59	—

evapotranspiration, storage, or exfiltration, it is hypothesized that exfiltration was the primary method of water loss (monitoring occurred during winter months when ET would be minimal and piezometers installed within the BRC would show water storage). As increasing isolated infiltration in karst areas is not recommended; the amount of water being lost from this system may be problematic in the future. Designers should keep this in mind when designing BMPs for karst areas and perhaps should design the BRC with gently sloping sides that can be lined with a compacted clay layer.

Fig. 3 displays pressure-corrected water levels in the deep piezometers for a storm in December 2007. The "uphill piezometer" was located approximately one-third of the distance between the inflow pipe and the overflow grate, whereas the "downhill piezometer" was located approximately two-thirds of the distance between the pipe and the grate. Both deep piezometers were on the BMP centerline and extended to the bottom of the BRC (approximately 1.83 m).

Fig. 3 shows the movement of water within the BRC for storm 5, which occurred on December 28–29, 2007. Analyses of the graph and personal observation of the BMP during multiple storm events provided useful information regarding BRC hydrology. As storm water entered the bioretention cell, it typically infiltrated rapidly in front of the inflow pipe, as opposed to flowing over the BMP surface and then infiltrating into the media. The graphs of the uphill and downhill piezometer water levels are similar, but separated by approximately 30 min. This suggests water moved rapidly to the bottom of the BMP and pooled before moving horizontally along the bottom of the BMP.

As shown in Fig. 3, runoff from storm 5 filtered through the treatment media within approximately 2 h (measured from the peak of the piezometer water level to the underdrain height of 30 cm), leading to an estimated vertical hydraulic conductivity of 11.8 cm/h. The actual hydraulic conductivity was much higher than the design value of 5 cm/h, likely because the BRC media was not compacted but instead was allowed to settle over time. The actual hydraulic conductivity will probably decrease over time as the media consolidates. The infiltrated storm water pooled to a depth of 38 cm in the uphill part of the BRC and 40 cm in the downhill part of the BRC. Outflow via the underdrains did not begin until water reached a height of 38 cm, and outflow ceased when water levels within the BMP dropped below 26 cm. Although the BRC was designed to include a 30-cm IWS zone, Fig. 3 shows water levels within the BMP continued to drop below 30 cm, indicating water was rapidly exfiltrating into the surrounding soil. Storm water had a very short residence time in the IWS; thus, denitrification in the IWS was likely minimal.

Hydrology results from the BRC were similar to findings by other research studies. Hunt et al. (2006) performed a hydrologic analysis of a bioretention cell constructed in high clay soils and designed with an IWS zone and an underdrain system. This design was similar to the BRC in this study, as the primary BMP design

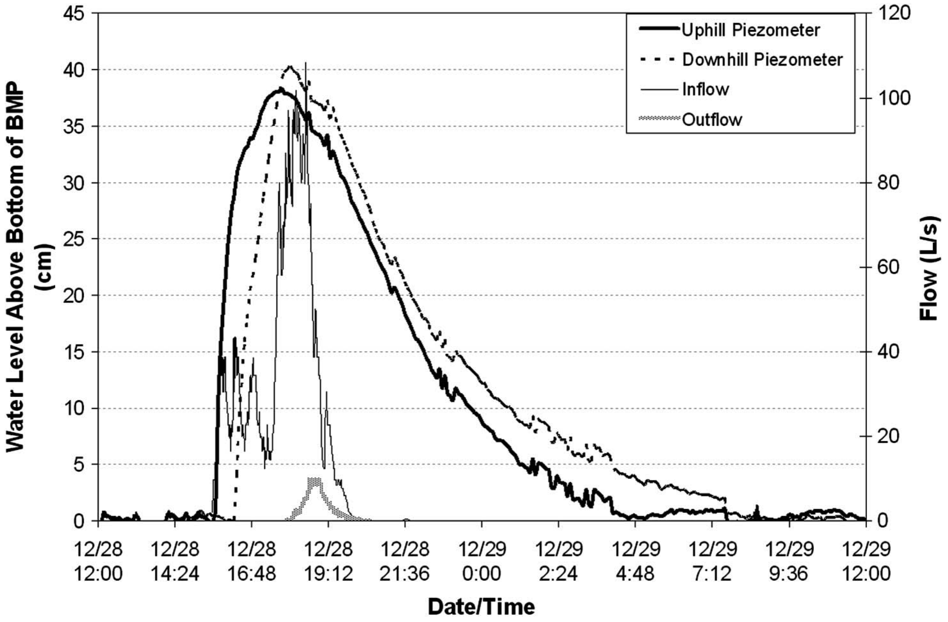

Fig. 3. Water levels within the bioretention cell, as well as inflow and outflow rates, during storm 5 on December 28–29, 2007

function was storm water treatment, not exfiltration. Their study reported an average volume reduction of 78%, which is somewhat lower than the results from the BRC, but still higher than would be expected in clay subsoils. Brown and Hunt (2011) reported volume reductions of 31–42% for unlined bioretention cells in clay soils. The fact that the studied BRC was deeper than the bioretention cells studied by Brown and Hunt (2011) and Hunt et al. (2006) likely contributed to the higher volume reductions. This hypothesis is supported by Brown and Hunt (2011), who showed that deeper bioretention cells tend to exfiltrate larger volumes of water than shallower cells.

Peak Flow Rates

As few runoff events produced outflow, there were few data to analyze regarding peak flow rate reduction. The median percent reduction of peak flow rate was 91%, considering only the five storms that produced outflow. For all storms monitored during the study period, inflow peak flow rates were significantly higher than outflow peak flow rates ($p = 6.03\text{E-}10$); however, when only analyzing the five storms that produced outflow, the BRC successfully reduced peak flow rates by 99% ($p = 0.15$). An important aspect of BMP performance is the treatment of frequent, small storm events. As there was a complete lack of outflow for the majority of monitored storms, an excellent overall reduction in peak flow rate was achieved.

Water Quality

When analyzing TN, TP, and SSC data, concentrations for events without outflow were designated “not applicable” and were not included in mean or median calculations or statistical tests. Loads for events without outflow were designated 0 kg, and were included in mean, median, and statistical calculations. As a result, all median and minimum values for constituent outflow loads for the BRC were 0 kg. Finally, water quality data were not collected for storms occurring between April 1, 2008, and May 10, 2008. Therefore, all results and conclusions regarding TN, TP, and SSC exclude storms 22–25.

Because so few storms produced outflow, median mass removal rates for all three constituents were 100%. If only storms that produced outflow were analyzed, the median mass removal rates were greater than 99%. The cumulative mass removal rates for suspended sediment, total nitrogen, and total phosphorus were all greater than 99%. Both TN and TP mass removal rates were negatively correlated to inflow volume ($\rho = 0.53$, $p = 0.006$ for both TN and TP), rather than inflow pollutant concentration or mass.

Suspended Sediment

The highest suspended sediment outflow concentration and load occurred during storm 20, which was the only storm that produced outflow in the form of surface overflow. The higher sediment concentration and load were likely attributable to a recent application of new mulch on the BMP surface and high inflow velocities. For storm events that produced outflow via the underdrains, the inflow and outflow concentrations were not significantly different, most likely because of the small data set ($n = 5$).

Storms 13 and 14 had high inflow suspended sediment concentrations when compared with previous storm events. These storms occurred on February 6, 2008, and February 13, 2008, respectively, amid icy weather. The Town of Blacksburg treats the municipal parking lots with a mixture of calcium chloride, magnesium chloride, and rock salt. Town streets are treated with a mixture of aggregate and deicing chemical (to be discussed in following sections). Increases in the amount of sediment and aggregate on the surface of the parking lots draining to the BMP were observed following icy weather. Therefore, the source of the increased suspended sediment during these storm events was likely the deicing mixture applied to the parking lots and/or aggregate that was tracked into the parking lot on vehicles.

Total SSC inflow and outflow loads were calculated for each storm event. Statistical analyses confirmed that the inflow loads of sediment entering the BRC were significantly greater than sediment loads leaving the BRC through outflow ($p = 2.98\text{E-}8$; $n = 24$). The percent mass removal was negatively correlated with inflow volume ($\rho = -0.53$, $p = 0.006$); therefore, the percent reduction in suspended sediment declined as the inflow volume increased. This finding is unsurprising, as higher inflow volumes would likely be more turbulent and would be more likely to result in surface overflow and higher outflow concentrations. There were no significant correlations of percent mass removal to either the inflow suspended sediment concentration or load.

In a study of a bioretention facility located in the Navy Yard parking lot, Washington, D.C., Glass and Bissouma (2005) measured a 98% reduction in total suspended solids, which is similar to the nearly 100% suspended sediment (SS) reduction found in this study. Brown and Hunt (2011) and Hatt et al. (2009) reported slightly lower total suspended solids (TSS) load reductions of 71–82% and 76–93%, respectively. These lower reductions are most likely attributable to the BRC being deeper; however, the difference in TSS and SS measurement may also contribute to these inconsistencies. Overall, the BRC substantially reduced the amount of suspended sediment entering the existing stormwater management system.

Total Nitrogen

The inflow and outflow concentrations of total nitrogen were not significantly different, although this result was likely affected by the small number of outflow events ($n = 3$). Storms 10 and 12 produced high inflow TN concentrations and loads, though the source of this nitrogen is unknown. Storm 20 had an unusually high outflow TN concentration, as this is the storm that produced overflow. The high concentration was most likely attributable to the application of new mulch six days prior to the storm, as discussed previously.

Table 2 summarizes the mass of nitrogen attributable to each media component. Although it is recognized that a certain amount of nitrogen is contributed by living plant material, the amount was considered small when compared with the amount supplied by the media. The leaf compost was added as a carbon source; however, it was also a significant source of nitrogen within the BMP. Carbon sources with low C : N ratios are more likely to release nitrogen into the system than a medium with a higher C : N ratio. Therefore, it is recommended that the organic matter chosen for any bioretention media have a high C : N ratio to reduce the amount of nitrogen released into the system.

Table 2 shows that the mass of nitrogen entering the BRC during the study period via inflow represented only a fraction of a percent in the overall BMP nitrogen balance. The sand nitrogen concentration was much higher than expected, but the reason for this is unknown. Likely causes include the sand parent material being naturally high in nitrogen or nitrogen compounds present in chemicals used at the quarry during the washing process. However, inquiries at the quarry did not reveal any clear nitrogen source.

Mulch was a sizeable contributor of TN, but the difference between the relative contribution at the beginning of the study period and the end of the study period was surprising. A mulch layer was applied to the BRC before monitoring commenced, and a refresher layer was applied in March 2008, toward the end of the study period. The second application of mulch, which is common practice for bioretention cells, increased the TN percent contribution for mulch by approximately 14%. If a new layer of mulch is applied every year and each layer adds approximately 4.3 kg of TN, the amount of TN added to the BRC attributable to mulch could be substantial. Not all of the nitrogen in the leaf compost and mulch would be in a labile form, as some organic forms are refractory. Additionally, the C : N ratio of mulch is sufficiently high that a net nitrogen uptake would occur during microbial degradation of the mulch (Tiquia et al. 2002).

The 99% TN mass removal efficiency of the BRC was much higher than results reported by other studies. Dietz and Clausen (2005) reported a TN removal rate of 32%, and Hunt et al. (2006) reported a rate of 40%. The difference between the removal efficiency achieved in this study and those reported by other studies is most likely attributable to the extremely high flow reductions and the large number of storm events that did not produce outflow from the BRC.

Total Phosphorus

Total phosphorus inflow concentrations ranged from 0.17 to 4.96 mg/l (Table 1). Differences between the inflow and outflow concentrations were not statistically significant. The two outliers identified in the inflow concentration data set occurred during storms 12 and 13. As mentioned previously, icy weather was prominent prior to these two storm events. The deicing chemical Liquidow (The Dow Chemical Company; Charlotte, North Carolina) was occasionally applied to the parking lot as part of a rock salt and aggregate mixture at an application rate of 26.2 L/t (Brian Long, Town of Blacksburg Department of Public Works, personal communication, Feb. 13, 2008). Liquidow is a 30–42% $CaCl_2$ solution containing 25 ppm phosphorus. Depending on the amount of chemical applied and the frequency of freezing precipitation, this may be a significant source of phosphorus in storm water runoff. For example, if 190 L of Liquidow were applied to the parking lot in conjunction with 7 t of rock salt and aggregate mixture, this would contribute approximately 4.7 g of TP. Assuming this mass of TP was available on the parking lot for storms 12 and 13, the resulting inflow concentrations could have been as high as 35.5 and 8.6 mg/L, respectively, indicating the Liquidow was likely the source of the high TP concentrations for those storm events.

High outflow TP concentrations occurred during storm 20 (2.25 mg/L). As discussed previously, this was most likely attributable to the newly applied mulch and the large inflow velocities. Table 2 summarizes the phosphorus mass in each media component at the beginning and end of the study period. Leaf compost was the most significant TP source, because of the high compost TP concentration, whereas topsoil was the second largest contributor. These results are not surprising, as phosphorus binds strongly with soil fines. TP added as a result of storm water inflow was negligible compared with the TP mass present in the BMP media.

Surprisingly, mulch was a considerable contributor to the overall TP budget. As shown in Table 2, the new mulch layer increased the percent contribution of TP by approximately 2%. A new mulch layer is commonly added to bioretention cells in the spring of each year; the old mulch layer is generally not removed because of labor, budget, and time constraints. In 10 years, approximately 27% of the TP within the BRC will be attributable to mulch additions,

Table 2. Total Nitrogen and Phosphorus Concentrations and Mass for Each Media Component Present in the Bioretention Cell during the Study Period

	Sand	Mulch (application 1)	Mulch (application 2)	Leaf compost	Top soil	Potting soil
TN concentration (mg/kg)	1,660	4,720	4,720	13,500	594	2,270
TN total mass (kg)	166	12.0	4.28	62.3	5.39	0.26
TP concentration (mg/kg)	10	200	200	900	200	400
TP total mass (kg)	0.998	0.508	0.181	4.08	1.81	0.047

assuming each additional mulch layer adds approximately 0.2 kg of TP and no mulch is removed.

To evaluate the potential of the bioretention media to store phosphorus, a Mehlich-III phosphorus test was conducted on all individual solid materials included in the bioretention media prior to the mixing and installation of the media. Certain ranges of Mehlich-phosphorus values correspond to levels of available phosphorus, as determined using the scale published by the Virginia Department of Conservation and Recreation (VADCR 2005). The Mehlich-III phosphorus values for the sand, mulch, leaf compost, top soil, and potting soil components of the bioretention media were "Very Low," "Medium," "Very High," "Low," and "High," respectively. Overall, the Mehlich-III value for the treatment media was "Very Low" on the basis of the mass-weighted average of the media as a whole.

Hunt et al. (2006) showed that a relationship exists between the amount of available phosphorus in the treatment media and the TP removal efficiency of a bioretention cell. As the BRC treatment media was very low in available phosphorus, it is unlikely that the BRC will export TP in the near future (Hunt et al. 2006).

As with TN, the TP removal rates reported by other research studies are lower than the rates reported in this study: Hunt et al. (2006) and Davis et al. (2001) reported TP load reductions of 65 and 80%, respectively. The difference between these average removal rates and the 99% produced in this study is most likely the lack of storms producing outflow as well as the greater cell depth. Additionally, Hunt et al. (2006) concluded the amount of available phosphorus in the treatment media greatly influences the TP removal rate of the bioretention system. Prior studies might have used a treatment media with a higher amount of available phosphorus, which could account for the higher removal rate observed in this study.

The drought potentially had numerous effects on BMP performance in reducing volume and improving storm water quality. Because of the drought, there were longer periods of dry weather between storm events, which likely increased the time for pollutant accumulation on the parking lots and increased inflow pollutant concentrations. Water-starved plants, dry treatment media, and parched surrounding soil could have increased the volume reduction capabilities of the BMP, producing higher volume reductions and pollutant removal rates than would be observed in years with normal rainfall amounts. Perhaps most importantly, the drought resulted in fewer precipitation events and a smaller data set during the study period than would be expected on the basis of the 30-year average.

The total precipitation, duration, average rainfall intensity, peak rainfall intensity, and the amount of time since the last precipitation event were determined for each monitored storm event. These variables were tested for correlation with the percent mass removal for all measured constituents (TN, TP, and SSC). It was determined that none of the storm characteristics listed were significantly correlated with the percent mass removal of any constituents; thus, there was little evidence that the features of an individual storm event affected the BRC pollutant removal efficiencies.

Conclusions

Overall, the bioretention cell was successful in reducing flow volumes and peak flow rates leaving the parking lot, as well as reducing the total mass of sediment, total nitrogen, and total phosphorus leaving the site. The cumulative volume reduction for the BRC was greater than 97%, likely attributable to water seeping out of the BMP walls through cracks in the surrounding soils. Of 28 storm events that produced inflow to the cell, only five storms produced outflow. Of these outflow events, only one produced overflow (water that bypassed the BMP). Therefore, the BRC effectively treated 97% of the water leaving the system. The BRC significantly reduced peak flow rates by 99%. This reduction was attributable primarily to the large amount of volume reduction; however, when only storms that produced inflow and outflow were considered, median peak flow reduction was 91%.

The bioretention cell achieved cumulative mass removals of greater than 99% for suspended sediment, total nitrogen, and total phosphorus, significantly reducing inflow pollutant loads. Study results indicated the BMP effectiveness at reducing storm water volume, peak runoff rates, and pollutant loadings to Stroubles Creek was strongly influenced by the total precipitation and maximum intensity of the storm event, as well as the inflow volume.

This study also highlighted the important influence of isolated pollution events in urban watersheds and "hidden" nutrient sources. Occasional, high phosphorus loads from the parking lots resulted from the use of deicing materials. Although high chloride concentrations are a recognized concern for water quality managers, an assessment should be conducted of all chemicals applied by public works departments to parking lots or open spaces to identify other possible sources of water pollutants. For example, decaking agents applied to road salts may contain high levels of phosphorus. Additionally, all materials used for bioretention construction should be tested for TN and TP prior to construction. Hunt and Lord (2006) recommended the use of washed sand; however, polyacrylamide, a potential nitrogen source, is frequently used to flocculate and remove fines as part of the washing process.

Observations made during the project indicate BMP design could be improved by increasing the length to width ratio of the BRC and planting a higher density of shrubs immediately downstream of the inflow. These design modifications would serve to reduce short-circuiting within the BRC, thus increasing treatment and reducing the occurrence of untreated overflow during high-intensity precipitation events.

The substantial loss of water through the BMP walls could be a cause for concern in the future. The karst geology of the area makes the infiltration of large amounts of water in one area undesirable. Following recommendations by VADCR, the bottom of the BMP was lined with clay to prevent this; however, large amounts of water still exfiltrated through the vertical walls of the BMP (VADCR 1999). This is an important finding, as it indicates that perhaps lining the bottom of a BMP is not enough to prevent the concentrated infiltration of collected runoff in a BMP. Those designing BMPs in karst areas should keep this in mind and possibly take additional measures to limit water losses from a BMP. For future installations in karst areas, it is recommended that the walls of BMPs be sloped such that they can be lined with a compacted clay layer (in addition to the bottom of the BMP) to prevent exfiltration. If there are spatial constraints that prevent this increase in surface area because of sloping the sides, a synthetic impermeable liner could be used in lieu of compacted clay.

The BRC was much deeper than the standard bioretention depth (0.6–1.2 m), which most likely caused the high volume reduction and consequent high pollutant load reductions. The results of this study, as well as those reported by Brown and Hunt (2011), suggest that deeper BMPs perform just as well, if not better than, shallower BMPs. This finding has implications especially for areas where space is limited, but a retrofit BMP is needed. If a deeper BMP with a smaller surface area can perform comparably to (or better than) a "standard-sized" BMP, this makes retrofits more feasible in areas with spatial constraints, especially in areas with high relief, as it is easier to acquire the necessary elevation changes for a deeper BMP. On the basis of the results of this study, bioretention is highly recommended as a method of treating urban storm water. However, as this study was conducted primarily during winter and spring months (and during a period of significant drought) different results may be found if data collected during summer and fall months (or during periods of normal rainfall patterns) were included in the analyses.

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