Comparing the Hydrologic Performance of a Bioretention Cell with Predevelopment Values

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Abstract: Bioretention cells have been found to improve the hydrologic and water quality performance of urban impervious areas. This study recorded continuous hydrologic data from a bioretention cell in Silver Spring, Maryland, over a period of 2 years. Two evaluation methods were used to assess bioretention performance, curve number (CN) volumetric analysis, and flow-duration flow regime analysis. CN-derived Woods B and C land uses were used to analyze cell volumetric performance, and data from a nearby forested stream were used to evaluate the cell flow regime. A CN of 75 was fit to the cell outflow with relation to rainfall depth. A larger cell, from 4.5 to 8.3% of the drainage area, was required to match the CN of woods land use. Flow duration comparisons between cell outflow and forested streamflow data suggested that bioretention may not match the predevelopment hydrologic regime despite performing similarly volumetrically. The overall natural hydrologic regime, not only peak flows and flow volume, of an area should be used both as a design factor as well as a performance metric for bioretention cells and other low-impact development (LID) facilities. **DOI: 10.1061/(ASCE)IR.1943-4774.0000504.** *© 2013 American Society of Civil Engineers.*

CE Database subject headings: Biological processes; Runoff curve number; Flow duration; Hydrology.

Author keywords: Bioretention; Hydrology; Curve number; Flow duration; Predevelopment.

Introduction

Urban ecosystems typically rely on an engineered system of channels and pipes to remove excess rainwater from impervious surfaces, such as roads, parking lots, and roofs, as quickly and efficiently as possible. These designs ensure public safety and health by preventing urban flooding. Because of the high percentage of impervious surfaces and the efficiency with which water is removed, very little infiltration into the ground occurs before this water runs off into surrounding areas. As a result, urban runoff delivers excess water to surrounding ecosystems. Because urban runoff moves rapidly, it also results in the mobilization and transport of various sediments, nutrients, and pollutants.

Many studies have shown that urban development negatively affects both the hydrology and water quality of surrounding streams and other natural water bodies (Barco et al. 2008). Developed urban runoff causes flashier hydrographs and is the source of many of the symptoms associated with the "Urban Stream Syndrome," which includes channelization of streams and rivers, increased nutrient loadings, and decreased biotic diversity (Walsh et al. 2005). While the loss of meanders in a stream reduces areas of denitrification, increased nutrient loadings can further increase phosphorous and nitrogen levels. Excess nutrients can lead to eutrophication and eventual dead zones. Eutrophication, in turn, can reduce biodiversity and overall natural water health.

Integrating bioretention facilities or "Rain Gardens" at the discharge points of impervious areas is one popular method of slowing and filtering urban runoff before it reaches surrounding ecosystems. These cells are part of the low-impact development (LID) effort to reduce the effects of development on the land and water environment by the most natural means possible. LID designs emphasize simplicity and incorporating green space within a development and within and around impervious surfaces. Following this philosophy, bioretention cells include layers of media to promote infiltration and incorporate vegetation to facilitate various water quality benefits as well as evapotranspiration between storm events.

Bioretention facilities may be sized based on the post and predevelopment curve number (CN) values for the drainage area, a design storm, and a predevelopment peak flow (The Prince George's County, Maryland, Dept. of Environmental Services 2007). Other sizing methods use the rational method by multiplying the "C" value for the drainage area by 5–7% of its area (Dietz and Clausen 2005). Regardless of the method, facilities are sized relative to how much runoff they will receive and how much volume is required to store a given design storm size. However, given that one of the core goals of LID design is to mimic predevelopment hydrologic regimes, using design storms as a guide to sizing bioretention cells may not be the most appropriate method. Long-term sustainability, water quality improvement, and hydrologic performance relative to relevant predevelopment hydrology should be the primary drivers in bioretention design.

To date, bioretention cells have been found to perform well hydrologically. One study found that 18% of 49 storm events were completely captured by the lined cells being monitored. In addition, peak flows entering bioretention facilities were reduced by 44–63% and were delayed significantly by the cells, usually producing outflow peak values a factor of two smaller than inflow peak values (Davis 2008). A study in North Carolina found similar reductions, reporting that all outflow volumes were less than 50% of the inflow volumes in unlined bioretention cells over the course of one year (Hunt et al. 2006). A peak reduction of 96% was seen in storm

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Note. This manuscript was submitted on July 7, 2011; approved on July 31, 2012; published online on August 7, 2012. Discussion period open until July 1, 2013; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Irrigation and Drainage Engineering***, Vol. 139, No. 2, February 1, 2013. © ASCE, ISSN 0733-9437/2013/2-124-130/$25.00.

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events producing less than 4 cm of rainfall in another study (Hunt et al. 2008).

A study of the hydrologic performance of six bioretention cells on the East Coast found that 20–50% of bioretention inflow was lost to exfiltration and evapotranspiration (Li et al. 2009). In addition, Li et al. (2009) noted that a larger cell-to-drainage area ratio and media volume improved bioretention hydrologic performance. A recent study quantified the storage capacity of bioretention cells based on both surrounding and cell media properties and on storage in the surface bowl. Quantitatively, this storage has been defined as the bioretention abstraction volume (BAV) (Davis et al. 2012). By comparing them with the measured volumetric performance of three bioretention cells, theoretical BAV values were validated. By employing BAV formulas, bioretention cell design can be improved, and hydrologic performance better defined.

Bioretention cells offer localized solutions to urban runoff with potential to reduce the causes of Urban Stream Syndrome. However, quantitative effectiveness of these storm water control measures (SCMs) is not available. A general success metric for an urban SCM is reducing postdevelopment conditions to states similar to predevelopment. Reaching predevelopment conditions, however, is difficult and ambitious, especially when bioretention cells serve only small portions of a watershed. As a result, their effect may not be apparent downstream. Investigating how bioretention cells perform compared to relevant forested watersheds could prove beneficial in implementing bioretention and other SCMs on a watershed level. Accordingly, the primary goal of this research is to better understand the long-term hydrologic performance of bioretention cells and how their performance compares with the often-cited goal of replicating predevelopment hydrology.

As reviewed previously, several studies have assessed bioretention performance solely on percent reductions from inflowing to outflowing water. While these reductions are important, a comparison with predevelopment values is a more valid measure of the ecological effectiveness of bioretention cells. A research gap now exists between how a cell will perform and what affect its performance may have on a watershed.

The current study aimed to fill this research gap by using CN analysis and relevant forested stream data to assess bioretention performance. Although CN analysis emphasizes volumetric performance, forested stream flow duration analysis focuses on evaluating the overall flow regime of the cell. Flood-frequency analysis was used in evaluating cell volumetric performance with respect to Woods C (CN = 75) and Woods B (CN = 73) land uses of the same area. Flow durations, and overall flow volumes from a nearby forested stream were compared with bioretention discharges to assess the overall hydrologic regime of the cell. These two evaluation methods (CN-analysis and predevelopment flow-duration analysis) suggest that whereas bioretention may approach the volumetric performance of Woods C land use, it fails to follow a predevelopment hydrologic regime.

Methods and Materials

Site Description

This study follows the performance of a bioretention cell installed in August 2005, in Silver Spring, Maryland. The cell was installed to mitigate and treat runoff from a health center parking lot. The cell has a surface area of approximately 102 m^2, which is approximately 2.8% of the entire drainage area of approximately 0.37 ha. According to a previous study, the cell media is 54% sand, 26% silt, and 20% clay (Li 2007). From these measurements, a porosity of 42% was estimated by adding the weighted-average porosities of each media type (sand, silt, and clay) (Fetter 2001).

Two monitoring stations were incorporated into the bioretention cell. The first station recorded the inflow level by using a 23-cm Parshall Flume and the rainfall by using an ISCO 674 0.25-mm tipping bucket rain gauge (Isco, Lincoln, NE). The second recorded the outflow water level through the underdrain by using a 15-cm Thel-Mar plug-in weir (Thel-Mar, Brevard, NC). Water levels were measured by using Teledyne ISCO 730 Bubbler Modules (Isco, Lincoln, NE) located in both the inflow and outflow monitors. More details about the site design and monitoring setup are presented in Li et al. (2009). Data were downloaded periodically from each station onto a laptop using the program Flowlink. Flowlink data were exported into a spreadsheet in which all analyses were done.

Monitoring Regime

The site was monitored continuously for 2 years. The data for six storm events from April 2009, through the beginning of June 2009, were lost due to the displacement of the outflow weir and power outages. Four other storms with outflow were also excluded from the data set due to obvious, incorrect readings from the outflow weir, resulting from movement of the weir and the bubbler line in the pipe. Snow events were excluded from the data set due to absence of rainfall depth and the complications snowmelt had on the data.

An individual storm event was defined as any rainfall that was preceded and followed by a dry period of at least 6 hours. All but one storm was analyzed under this assumption. On January 25, 2010, a 0.20 cm storm event occurred a little over 8 h after a larger, 1.22 cm storm. Outflow occurred through the duration of both events, making it difficult to separate the event outflows. Because the rainfall depth of the second storm event was significantly below the cell's field-derived bioretention abstraction volume of 17.3 m^3 (Davis et al. 2012), no outflow should have been produced by this storm alone. Therefore, these storms were combined into one event with a total rainfall depth of 1.42 cm.

The monitoring devices measured in 2-min increments; to make the data more manageable, the points were consolidated into 4-min increments. Consecutive rainfall levels were summed; the inflow and outflow levels, however, were averaged to get 4-min values. All plots and other parameters and metrics were computed using these 4-min increment values. To estimate the inflow and outflow volumes, the recorded flow rates [Q(t)] were integrated with respect to time:

$$V = \int_{t1}^{t2} Q(t)dt = \sum Q(t)\Delta t \tag{1}$$

Hydrographs and flow-duration curves were used to analyze individual storm events. Flow-duration curves were synthesized by ranking all 4-min inflow and outflow flow rate values individually from highest to lowest for the entire duration of interest. The ranked values were then plotted against time, resulting in inflow and outflow flow-duration curves.

Forested Stream Data

For comparison with the bioretention cell, streamflow data were acquired from the USGS for a small, completely forested stream, Pond Branch. Current streamflow data in 15-min increments were downloaded from http://waterdata.usgs.gov/md/nwis/nwisman?site_no=01583570 (USGS 2010); older streamflow data were provided by Jon Dillow of the USGS (J. J. Dillow, personal communication, 2010). This stream is located in Oregon Ridge Park,

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which is 3.7 km west of Cockeysville, Maryland, and approximately 72 km northeast of the cell. The Pond Branch stream specifically has a drainage area of approximately 31 ha. Representative rain data for the Oregon Ridge Park were obtained from a rain gauge approximately 1.2 km north of the flow gauge. Rain data from May 2008 through May 2010 were obtained from both USGS and The Center for Urban Environmental Research and Education with the help of Phillip Larson (P. Larson, personal communication, 2009).

Pond Branch streamflow data from May 2008, through May 2010, were also organized into a flow-duration curve. Base flow was removed from the forested stream data by using the Lynne-Hollick filtering method (Nathan and McMahon 1990; Eckhardt 2005):

$$b_k = \alpha b_{k-1} + \frac{(1-\alpha)}{2}(y_k + y_{k-1}) \tag{2}$$

where b_k and b_{k-1} = base flow values at times k and $k-1$; y_k and y_{k-1} = total streamflow at times k and $k-1$; and α = filter parameter. As specified by a number of sources, an α of 0.925 was used (Nathan and McMahon 1990; Chapman 1991; Eckhardt 2005). For comparisons, flow durations were normalized by their respective drainage areas.

Streamflow volumes were also computed over the duration of the 2-year study. The integral of the streamflow data was estimated with the trapezoidal method, as was done for the cell inflow and outflow volumes in Eq. (1).

Data Processing and Analysis

To judge the performance of the bioretention cell, curve number estimates were used to predict the behavior of three different land uses given the same drainage area as the cell. Curve number generated Woods B, Woods C, and pavement areas were simulated given the rainfall distribution of the current data set and CN values found in McCuen (2005). Runoff depths from each area were estimated by using the Soil Conservation Service (SCS) rainfall-runoff equation (McCuen 2005).

$$Q = \frac{(P-0.2S)^2}{P+0.8S} \tag{3}$$

where Q = runoff depth (cm); P = rainfall depth (cm); and S = potential maximum soil moisture retention (cm).

S is a function of the CN and was found by using the following equation:

$$S = \frac{1{,}000}{\mathrm{CN}} - 10 \tag{4}$$

Runoff ratios [as calculated in Eqs. (3) and (4)] were also used in a least-squares analysis of all measured storm events to determine a curve number for the Silver Spring bioretention cell.

Exceedance plots were used to compare the rainfall distributions and runoff reduction ratios [the ratio of cell outflow volume over cell inflow volume, f(v)] from the bioretention monitoring and from CN-generated land uses. Data were ranked from highest to lowest for each land use. Corresponding nonexceedance probabilities and Z-values were then calculated for each value based on its rank, as done in previous bioretention studies (Li and Davis 2009). Z-values were then used to compute corresponding χ^2 values, according to Iman (1977). Once χ^2 values were obtained, they were compared with values in the chi-square distribution table (Ayyub and McCuen 2003) with a $\upsilon = 1$. If the computed values corresponded to a $p < 0.05$, the $H_o{:}p_1 = p_2$ was rejected, and the two regression lines were assumed to be statistically different.

Hydrologic Soil Types

As determined by the Natural Resources Conservation Service (NRCS) hydrologic soil group map, both the bioretention site and Pond Branch lie in areas with hydrologic soil Group B (USDA-NRCS 2012). Therefore a Woods B CN of 73 should describe the predevelopment hydrology for the cell site and the current hydrology for Pond Branch.

Results and Discussion

Rainfall Distribution

A total of 197 rainfall events were recorded at the Silver Spring site from May 2008 through April 2010. Fifty-two events produced only 0.025 cm of rainfall (0.01 in., corresponding to one tip of the rain gauge). The condensation of moisture or equipment malfunctions appeared to have caused some of these small events and they all were removed from the data set. Sevruk (1996) made similar assumptions about single-tip events. Because these events did not create any runoff or contribute to inflow to the cell, they were assumed negligible. Therefore, a total of 145 rainfall events were analyzed for this study.

Rainfall depth, duration, and frequency were analyzed to examine the distribution of events measured. The data set from the bioretention cell was within 10% of the Maryland average distributions for the summed rainfall depth categories (shown in the bottom row of Table 1). The cell data differed from the Maryland averages in medium storms (0.255–0.635 cm), demonstrating 7.5% more medium storm events. Storm events producing >2.54 cm (large storms) accounted for approximately 14% of all storm events, according to Maryland averages; larger storm events accounted for only 9% of the Silver Spring cell data set.

Comparing the sum column in Table 1, the storm distributions for the current cell data set are all within 15% of the Maryland average, according to event duration. The current data set showed the greatest deviation from the Maryland average distribution in event durations of 7–13 h and 13–24 h with differences of 7.3 and −6.5%, respectively.

Of the 145 events used to evaluate the overall rainfall distribution for the current study, 21 of them were consumed by the initial abstraction of the parking lot (7% of events). These events were excluded from the bioretention cell analysis because no runoff reached the cell. With these events removed, the current study observed 130 storm events producing runoff volume that entered the bioretention cell, 26% of which were small storm events (0.0254–0.254 cm). Therefore, although the site experienced rainfall approximately representative of the Maryland average distribution, storm events actually entering the bioretention cell had fewer small storms.

Volume: Cell Storage and Curve Number Estimation

Davis et al. (2012) published a detailed discussion about bioretention volumetric storage capacity defined as the BAV. Based on the media properties of the Silver Spring cell, an average BAV of 21.5 m^3 was calculated, which agrees well with the data-derived BAV of 18.8 m^3 (Davis et al. 2012). This corresponds to about half of the cell's porosity and 20% of the total cell volume.

Overall, the cell reduced the Silver Spring site from an estimated CN = 96, based on cell input runoff, to a value of CN = 75, calculated by using cell underdrain output. Fig. 1 shows an exceedance plot of rainfall-runoff ratio values for the bioretention cell, Woods C (CN = 73), and Woods B (CN = 60). Although the cell did not perform as well volumetrically, its exceedance plot

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Table 1. Depth-Duration Summary of Rainfall Distribution Based on Rainfall Depth and Event Duration

Event duration (h)		Rainfall depth (cm) 0.0254–0.254 cm	0.255–0.635 cm	0.636–1.27 cm	1.28–2.54 cm	>2.54 cm	Sum
0–2	CD	0.214[a]	0.048[a]	0.021[a]	0.014[c]	0[c]	0.297[b]
		31, 31[a]	7, 7[a]	3, 3[a]	2, 0[c]	0, 0[c]	43, 41[b]
	MD	0.2857[a]	0.214[a]	0.0167[a]	0.0043[c]	0.0008[c]	0.3289[b]
2–3	CD	0.014[a]	0.034[a]	0.014[a]	0.014[c]	0[c]	0.0795[b]
		2, 2[a]	5, 5[a]	2, 2[a]	2, 0[c]	0, 0[c]	11, 9[b]
	MD	0.0164[a]	0.0257[a]	0.221[a]	0.0089[c]	0.0025[c]	0.0756[b]
3–4	CD	0.028[a]	0.014[a]	0.007[a]	0[c]	0[c]	0.0483[a]
		4, 4[a]	2, 2[a]	1, 1[a]	0, 0[c]	0, 0[c]	7, 7[a]
	MD	0.0085[a]	0.0223[a]	0.0198[a]	0.0083[b]	0.0038[c]	0.0627[a]
4–7	CD	0.069[a]	0.062[a]	0.028[b]	0.021[c]	0[c]	0.179[b]
		10, 10[a]	9, 9[a]	4, 2[b]	3, 0[c]	0, 0[c]	26, 21[b]
	MD	0.0099[a]	0.351[a]	0.475[b]	0.0221[c]	0.0087[c]	0.1233[b]
7–13	CD	0.021[a]	0.048[a]	0.083[a]	0.083[b]	0.028[c]	0.255[b]
		3, 3[a]	7, 7[a]	12, 12[a]	11, 3[b]	4, 0[c]	37, 25[b]
	MD	0.0058[a]	0.0337[a]	0.0629[a]	0.0528[b]	0.0266[c]	0.1818[b]
13–24	CD	0.007[a]	0.014[a]	0.021[a]	0.021[b]	0.028[c]	0.0966[b]
		1, 1[a]	2, 2[a]	3, 3[a]	4, 3[b]	4, 0[c]	14, 9[b]
	MD	0.0024[a]	0.007[a]	0.0397[a]	0.0611[b]	0.0515[c]	0.1617[b]
>24	CD	0[a]	0[a]	0.007[a]	0.007[b]	0.034[c]	0.0483[b]
		0, 0[a]	0, 0[a]	1, 1[a]	1, 0[b]	5, 0[c]	7, 1[b]
	MD	0[a]	0.0009[a]	0.0043[a]	0.0172[b]	0.0435[c]	0.0659[b]
Sum	CD	0.352[a]	0.221[a]	0.179[b]	0.159[b]	0.090[c]	1.0[b]
		51, 51[a]	32, 32[a]	26, 24[b]	23, 6[b]	13, 0[c]	145, 113[b]
	MD	0.3287[a]	0.1461[a]	0.213[b]	0.1747[b]	0.1374[c]	1[b]

Note: Current data are labeled CD; Maryland averages (Kreeb and McCuen 2003) are labeled MD. The top number in each CD box represents the fraction of total storm events that matched the designated storm depth and duration. The number in the bottom left of each box represents the total number of storms of that category. The number in the bottom right of each box represents all storms completely contained (producing no outflow from the bioretention cell).
[a]Storm categories for which all storms of that rainfall depth and duration were completely captured by the cell.
[b]Storm categories for which some storms produced cell outflow while others did not.
[c]Storm categories only containing storms producing outflow from the cell.

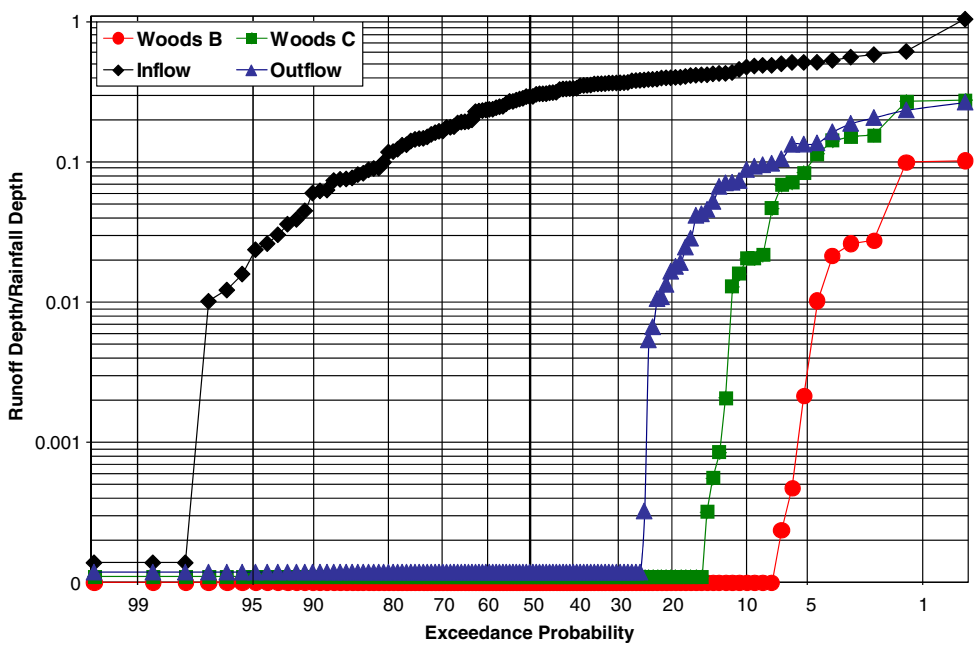

Fig. 1. Probability of runoff depth/rainfall depth for the Silver Spring cell inflow, outflow, Woods C (CN = 73), and Woods B (CN = 60)

followed the same shape as the CN-derived plots. From a runoff volume/depth perspective, the site approached a Woods C drainage area (CN = 73) of the same size. Based on curve number analysis, a predicted 15% of all recorded storm events from the current study would have produced outflow in land use Woods C, as opposed to 25% as measured for the cell. Only 7.1% of all recorded storm events would have produced outflow in the Woods B (CN = 60) drainage area.

By using the BAV storage capacity of 20% of the total cell volume, relative bioretention cell volumes were estimated for different land uses based on the maximum storm size completely captured by each. Table 2 summarizes these values. For the Silver Spring site

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Table 2. Bioretention Cell Volumes Required to Capture Same Size Storm Events as Woods C and Woods B Based on Curve Number Analysis

Location type	Maximum rainfall depth producing no outflow	Corresponding inflow volume		Required bioretention media volume at 20%	Cell to drainage area ratio at 90 cm depth
	cm	L	m^3	m^3	%
Silver Spring bioretention	1.27	18,800	18.8	94.1	2.81
Woods C (CN = 73)	1.96	30,000	30.0	150	4.48
Woods B (CN = 60)	3.51	55,300	55.3	276	8.24
Pavement (CN = 98)	0.127	235	0.2	1	0.04

to mitigate the same volume of runoff as a Woods C land use (CN = 73) with the same drainage area, a 150 m^3 cell would be required. Assuming a depth of 0.9 m (the same as the current cell), a Woods C cell would require an area of 167 m^2, or approximately 4.5% of the total drainage area, which is within the typical cell/drainage area ratio range of 3–5% (Davis 2008). A cell volume of 276 m^3 and an area of 307 m^2, representing 8.3% of the total drainage area, would be required to control the same volume of water as a Woods B (CN = 60). While not unfeasible, this represents a significant increase in area that must be dedicated to the bioretention infrastructure. A greater media depth could correspondingly reduce the area requirement.

While the cell did not perform as well as the Woods C and Woods C derived drainage areas, its exceedance plot behaved similarly. Once the BAV of approximately 20% of cell volume was filled, the runoff-rainfall ratio increased linearly. Therefore, no flow occurred between storm events, which is not the case for natural streams that are groundwater fed. Although the cell hydrologically behaved as a CN-derived area, this BAV behavior may not best mimic the natural hydrology of the area.

Comparing Cell and Pond Branch Volumetric Trends

Whereas estimated base flow was removed from all storm events, shallow infiltration in the Pond Branch drainage area may have also fed stream flow. Therefore, although the forested area provided greater infiltration and runoff mitigation, Pond Branch produced a constant flow because it was groundwater-fed. This constant flow contrasts the Woods B CN-derived land use, which only produced flow after the initial abstraction was met. Therefore, while Pond Branch should exhibit Woods B hydrologic behavior, its hydrologic regime may be quite different in reality.

Soil group and the cover complex define curve number models (McCuen 2005). These models assume no flow occurs between storm events. Pond Branch, on the other hand, as a stream, exhibits a constant base flow and is fed by both runoff and shallow groundwater from the surrounding land. Because Pond Branch is a stream, it represents the endpoint for all runoff in its watershed, unlike the CN models, which estimate the infiltrative properties of a given area. The CN models do not account for the time of concentration of an area or base flow; they estimate runoff depths solely on the initial abstraction (I_a) and soil moisture retention (S) properties of the land use type; only producing flow after a given amount of rainfall.

Idealistically, bioretention cells are designed to imitate the infiltration of forested areas, reducing runoff flow and volume to urban streams. Comparisons with the Pond Branch site suggested that predevelopment hydrologic goals may be more complex than the simple volume reduction implied by CN analysis, and may be watershed dependent. Because bioretention cells are designed to be the collecting point of all runoff for a given area, perhaps they should be designed to exhibit more stream-like conditions, with a constant base flow (DeBusk et al. 2011). However, the role of a given cell should depend on the hydrology of the watershed in which it is placed.

Comparison of Flow-Duration Curves

Previous stream studies found natural streams had smaller discharges, smaller differences in flow when comparing drought and flood events, and slower responses to rainfall and longer flow durations than channelized streams (Shields et al. 1994; Konrad and Booth 2005). Urban streams often have reduced base flow and increased flow from storm runoff attributable to less infiltration to groundwater in surrounding impervious areas (Konrad and Booth 2005). This imbalance in flow causes unstable stream flow, with very little or no flow between storm events and high flows (often above critical flow, which can cause erosion) during storm events (Konrad and Booth 2005; Shields et al. 2008).

Flow-duration curves (normalized by drainage area, as mm/day) comparing cell inflow, cell outflow, and forested stream flow are compiled in Fig. 2. With an estimated base flow removed, the cumulative duration of flow for the Pond Branch data was still more than 13,000 h over the course of the two-year study period. This duration was much longer than the respective bioretention inflow and outflow durations of 635 and 342 h. Although Pond Branch flow data were fairly continuous, the bioretention data represented flows solely during or directly after storm events. Flow rates were zero all other times; there was no continuous flow from the cell between rainfall events, unless events were very close together.

The maximum flow rate for inflow from the bioretention drainage area was 933 mm/day, for outflow 159 mm/day, and for Pond Branch 88 mm/day. The inflow maximum was almost ten times that of Pond Branch, demonstrating the effect of development, and the outflow maximum value was nearly double that of Pond Branch. These large differences between cell outflow and Pond

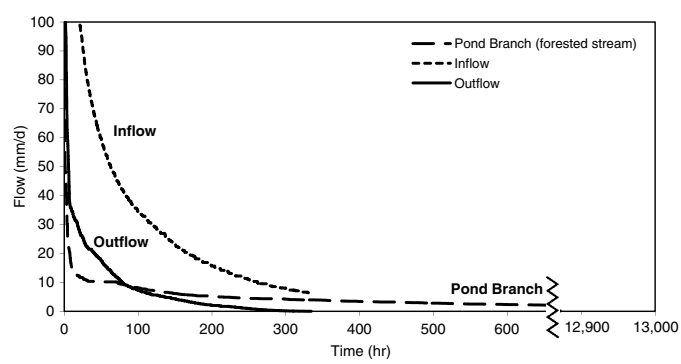

Fig. 2. Flow-duration curves for the Silver Spring cell inflow, the Silver Spring cell outflow, and the Pond Branch Stream; cell inflow, cell outflow, and Pond Branch flows had peak flows and durations of 935 mm/days and 635 h; 159 mm/days and 342 h; and approximately 88.1 mm/day and 13,200 h, respectively, from 2 years of monitoring

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Branch peak flows were attributable to increased infiltration and mitigation in the forested Pond Branch drainage area (King et al. 2009). Whereas the cell reduced the overall peak flow of the site by 83%, this normalized peak discharge was still almost twice that of the selected predevelopment landscape.

The bioretention outflow curve descends faster than the inflow curve. Discharge values were consistently below inflow values, indicating that the cell reduced the inflow rate and exposure duration. The outflow curve exceeds the maximum Pond Branch value from 0–2 h. Storm events of approximately the same size were producing more high flow rates (>13 mm/day) in the cell than in the Pond Branch stream.

All three curves were initially very steep. However, the Pond Branch curve has a much shorter, steeper decline, indicating fairly constant flow rates over most of the course of the study. The Pond Branch flows leveled out after a duration of 15.5 h, falling to a flow rate of 13 mm/day. The cell inflow and outflow only reached 117 and 31 mm/day, respectively, after 15.5 h.

At approximately 82 h, the cell outflow curve intersects and dips below the Pond Branch curve, at a flow rate of approximately 9.5 mm/day. After this point, the bioretention outflow continues to decrease at a steeper slope than the Pond Branch, reaching zero flow after approximately 252 h.

An enlarged graph of the cell outflow and Pond Branch flow-duration curves better highlights the comparison between the two (Fig. 3). The greatest difference between the curves exists between 8 h and approximately 50 h. During this time, the Pond Branch reached a slow, steady decline in flow rate after 15.5 h. The cell outflow remained higher for longer. Pond Branch appeared to mitigate larger, more intense storm events more effectively than the cell, resulting in lower peak flows and fewer high flows overall, reflecting the expected behavior of a forested stream (Konrad and Booth 2005).

As mentioned previously, one primary difference between urban and forested streams is the distribution of flow between base flow and storm flow (Konrad and Booth 2005; Shields et al. 2008). Base flow stabilizes streamflow, creating a suitable habitat for more organisms. However, when base flow is reduced and storm flow increased, the stream becomes unstable, forcing inhabitants to adapt to extreme conditions of low and high flows (Konrad and Booth 2005). This imbalance also causes channel erosion and incision; which in turn, reduces stream water quality mitigation and habitat suitability (Konrad and Booth 2005; Walsh et al. 2005; Spänhoff and Arle 2007; Shields et al. 2008). The Pond Branch stream represents a healthy, forested stream, whereas the Silver Spring cell is designed to be a buffer between urban development and the surrounding aquatic ecosystem. A smooth, moderate flow duration curve, without high peaks is critical to providing a steady base flow and habitat.

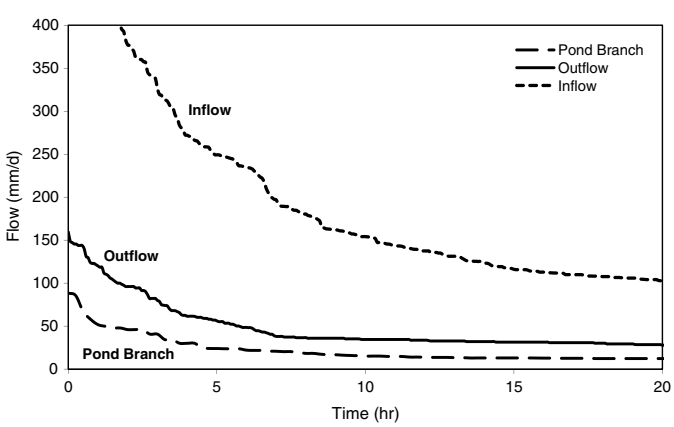

Fig. 3. Enlargement of flow-duration curves for Silver Spring inflow, outflow, and Pond Branch stream

Because the cell produced no flow between storm events, it was difficult to compare its total flow volume with that of the Pond Branch stream, which has continuous flow. Because the Pond Branch stream had a constant flow, its total flow duration was longer (13,000 h) and therefore, had a greater total flow volume of 275 mm (vis-à-vis 114 mm outflowing from the cell). However, considering only the total duration of flow entering the cell (635 h) the flow volume in Pond Branch was only 142 mm. Finally, the Pond Branch flow volume after 342 h, the total duration of flow leaving the cell, was 104 mm, which was close to the cell outflow volume of 114 mm. This suggests that the overall storm flow duration in Pond Branch may be closer to the cell inflow duration. Pond Branch also produced flow in storms that produced no outflow in the cell. All resulting flow volumes are summarized in Table 3.

To provide additional insight, the storm events causing the maximum flow rates for each system were also analyzed. The maximum flow rate for Pond Branch was 88 mm/day and occurred on September 27, 2008, at approximately 4 p.m., which was recorded as a 1.57 cm storm in Baltimore. While, this was not an exceptionally large storm, it did follow Hurricane Hanna, which occurred on September 6, 2008. A heightened water table may have reduced infiltration storage, causing more water to runoff into the stream. The maximum peak values for the bioretention inflow and outflow did not occur in the same storm events. The maximum inflow value (933 mm/day) occurred during a May 8, 2008, storm, which lasted 1.31 days and had a rainfall depth of 12.5 cm. This event also provided a 4-min rainfall depth of 0.533 cm, which was the maximum 4-min rainfall intensity recorded over the course of the study. The maximum outflow rate (159 mm/day) occurred during Hurricane Hanna on September 6, 2008, which lasted 0.45 days and produced 7.34 cm of rainfall. The peak inflow rate for this storm event was 666 mm/day.

These data suggest that whereas the inflow rates may depend heavily on the intensities within a storm event, the bioretention outflow and Pond Branch discharges are buffered by the watershed, travel time, and media infiltration, and therefore, are more dependent on total rainfall depth rather than intensity. The bioretention cell and Pond Branch both promote storage and infiltration before outflow occurs, dampening the effect of rainfall intensity. With rainfall depth as a primary performance-controlling factor, the storage capacity of the cell is important. A larger cell has a greater runoff holding capacity and therefore, will more efficiently dampen the effects of rainfall intensity.

To better mimic natural, downstream behavior, predevelopment flow-duration curves, in addition to hydrographs should be used to size and evaluate LID facilities such as bioretention cells. This method of sizing, flow-duration control, aims to meet predevelopment peak flows and overall flow regimes (Palhegyi 2010). Bioretention cells should be designed based on the predevelopment flow regime of the receiving natural waters. Assuming the

Table 3. Overall Volumes of Runoff from Bioretention Cell Inflow, Cell Outflow, and Pond Branch Given Different Possible Flow Durations over 2 Years Continuous Measurement

Flow source	Total duration (h)	Peak flow rate (mm/day)	Total volume (mm)	Volume after 653 h (mm)	Volume after 342 h (mm)
Cell Inflow	653	935	552	552	524
Cell Outflow	342	159	114	114	114
Pond Branch	13,000	88.1	275	142	104

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predevelopment receiving waters of the Silver Spring cell are similar to those analyzed at the Pond Branch site, the cell was not successful at reproducing a predevelopment flow regime. To better match predevelopment flow-durations, greater storage, and lower maximum discharge rates are necessary, lengthening flow-duration in the process.

Conclusions

The monitored bioretention facility in Silver Spring, Maryland, successfully reduced runoff volumes, flow rates, and flow durations from the developed the drainage area. Rather than directly responding to rainfall and rainfall intensity like the cell inflow, the cell outflow depends on media saturation and ponding depth. This indirect relationship with rainfall makes outflow rates significantly smaller and more constant than inflow rates. As noted in previous work, media volume will control runoff storage volume. From a CN volumetric analysis, assuming the same cell depth, the current cell-to-drainage area ratio would have to be increased from 2.7 to 4.5% for the facility to perform the same hydrologically as a Woods C land use; to achieve Woods B values, a ratio of 8.3% would be needed.

While CNs are good guides and indicators of performance, they should not be the only performance tools used to define predevelopment values. Flow duration analysis showed that actual forested stream hydrology is much more stable than bioretention hydrology. If bioretention cells are to be a hydrologic solution to urban hydrology problems, they must closely mimic the actual predevelopment watershed they sit on. As a result, relevant predevelopment hydrology should be used in the design of bioretention cells. Although this exact method of design may be unattainable because of little knowledge of actual predevelopment values or groundwater behavior, appropriate goals could be established given a basic idea of the necessary hydrologic regime.

Acknowledgments

This project was partially supported by the Cooperative Institute for Coastal and Estuarine Environmental Technology, CICEET, NOAA Grant Number NA06N054190167. Appreciation is extended to the Montgomery County, Maryland, Dept. of Environmental Protection for supporting the Silver Spring bioretention site and to the USGS for providing Pond Branch stream flow and rainfall data.

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