Mitigation of Impervious Surface Hydrology Using Bioretention in North Carolina and Maryland

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Abstract: As an increasingly adopted storm water best management practice to remedy hydrologic impairment from urban imperviousness, bioretention facilities need rigorous field performance research and monitoring to confirm performance and improve design and maintenance recommendations. This study investigated hydrologic performance at six bioretention cells in Maryland [College Park (CP), a 181 m^2 cell, 50–80 cm media depth, monitored for 22 events, and Silver Spring (SS), a 102 m^2 cell, 90 cm media depth, monitored for 60 events] and North Carolina [Greensboro (G1 and G2), each approximately 317 m^2, 120 cm media depth, both monitored for 46 events, and Louisburg (L1=surface area of 162 m^2, L2=surface area of 99 m^2); each had 50–60 cm fill depths, monitored for 31 and 33 events, respectively] over 10–15 month periods. Outflow from each cell was recorded and inflow was either recorded or calculated from rainfall data. In Louisburg, L2 was lined with an impermeable membrane to eliminate exfiltration while L1 was unlined to allow both exfiltration and evapotranspiration. Results indicate that bioretention facilities can achieve substantial hydrologic benefits through delaying and reducing peak flows and decreasing runoff volume. A large cell media volume: drainage area ratio, and adjustments to the drainage configuration appear to improve the performance. Media layer depth may be the primary design parameter controlling hydrologic performance. Performance diminishes as rainfall depths increase and rainfall durations become longer. Annual water budget analysis suggests that approximately 20–50% of runoff entering the bioretention cells was lost to exfiltration and evapotranspiration.

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Introduction

Increases in impervious land area resulting from urban development can have enormous repercussions on the hydrologic cycle and corresponding water quality. Land development significantly alters watershed hydrology, reducing the vegetative interception of rainfall, infiltration, and groundwater recharge, with concomitant increases in surface runoff. The conversion to rapid runoff renders the developed watershed more fragile against floods and droughts. As urban storm water runoff flows across impervious areas, it also collects and accumulates pollutants that are detrimental to water quality.

In the past several years, many best management practices (BMPs) have been developed and deployed to reduce these adverse effects as part of the low impact development (LID) philosophy. One primary category of BMPs relies on (in)filtration through pervious media, which allows collected storm water to percolate as a treatment. Beneath the media, the treated water may infiltrate, providing groundwater recharge, or it is collected in an underdrain for eventual discharge to the local receiving stream. Among these filtration/infiltration BMPs, bioretention, also known as "rain gardens" is being increasingly adopted (Davis 2005; Dietz 2007). Bioretention generally consists of a pervious soil media layer covered with a thin layer of hardwood mulch. A variety of vegetative species (grasses, shrubs, and small trees) are planted to promote evapotranspiration, biological activity, and pollutant uptake, as well as to maintain soil porosity and permeability.

Various studies have documented bioretention performance in improving both water quality and watershed hydrology (Davis et al. 2001, 2003; Dietz and Clausen 2005, 2006; Hunt et al. 2006, 2008; Davis 2007, 2008). However, quantifying the hydrologic benefits of bioretention facilities in field situations is complicated by design variation and rainfall characteristic variability. This study presents field results for six bioretention facilities in Maryland and North Carolina, United States, with particular emphasis on peak flow mitigation, outflow volume reduction, and time to peak impacts. At one pair of cells, evapotranspiration and infiltration contributions are separately estimated. These research results provide opportunities to document hydrologic performance and to improve field bioretention design and maintenance procedures.

Methodology

Site Descriptions

A summary of principal design elements for all six bioretention cells (four in North Carolina and two in Maryland) is presented in

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Table 1. Descriptions of Bioretention Cells Examined in Maryland and North Carolina

	CP	SS	G1	G2	L1	L2
Location	College Park, Md.	Silver Spring, Md.	Greensboro, N.C.	Greensboro, N.C.	Louisburg, N.C.	Louisburg, N.C.
Watershed	Anacostia	Anacostia	Cape Fear	Cape Fear	Tar-Pamlico	Tar-Pamlico
Year built	2004	2006	2001	2001	2004	2004
Watershed size (ha)	0.26	0.45	0.50	0.48	0.36	0.22
Watershed composition	Parking lot +roadway	Parking lot +driveway	Parking lot	Rooftop+ parking lot	Parking lot	Parking lot+ ball field
Surface to drainage area ratio (%)	6	2[a]	5	5	4.5	4.5
General shape	Trapezoid	Triangle	Rectangle	Rectangle	Oval	Rectangle
Ponding depth (cm)	10–34	30	23	23	15	15
Fill media depth (m)	0.5–0.8	0.9	1.2	1.2	0.5–0.6	0.5–0.6
Soil texture[b]	Sandy loam	Sandy clay loam	Loamy sand	Loamy sand	Sandy loam	Sandy loam
Organic matter[b] (%)	12	5.7	3	3	5	5
pH[b]	7.3	7.7	—	—	—	—
Vegetation cover	Trees/shrubs/ mulch	Trees/shrubs/ mulch	Trees/shrubs/ mulch	Trees/shrubs/ mulch	Trees/shrubs/ mulch	Trees/shrubs/ mulch
Underdrain no. & size	2@15 cm[c]	2@15 cm[c]	2@15 cm[c]	2@15 cm[c]	2@15 cm[d]	2@15 cm[d]
Distinguishing features	—	Possibly treat smaller area[a]	Internal storage zone 60-cm deep	—	—	Lined by imperm. membrane

[a]The design area of 0.45 ha may not have been met. Field observation indicated flow routed elsewhere during some events.

[b]Tests for Maryland sites conducted by the University of Delaware Soil Testing Program. In North Carolina, these tests were run by the NC Department of Agriculture and Consumer Services' Soil Testing Laboratory.

[c]Perforated PVC.

[d]Corrugated plastic pipe.

Table 1. The surface area: watershed size ratio ranged from 2 to 6% for the cells and all were designed with pool storage of 0.6–1.2 cm of runoff over the respective drainage areas. All six treated heavily impervious watersheds consisting principally of asphalt parking lots with some rooftop and open space. Media depths ranged from relatively shallow (0.5 m) to somewhat deep (1.2 m). Soil textures were similar among the six cells, and five of the six employed a conventional drainage system (i.e., no induced saturation or internal water storage zone). One of the six cells (L2 in Louisburg) was lined with an impermeable membrane to prevent exfiltration. Each cell was located in a nutrient sensitive watershed and monitoring occurred within 3 years of each cell's construction.

In Greensboro, G1 has a 0.6 m internal storage zone (ISZ). The ISZ was created by placing an elbow turn where the underdrain entered the storm drain network. This upturned pipe forced temporary saturation within this lower zone and prohibited outflow until the internal water level reached the level of the elbow. This design technique promotes anaerobic conditions for water quality improvement and anecdotally affects hydrologic mitigation.

Monitoring Methodology

All cells were monitored using similar approaches. Monitoring equipment, instrumentation, and methods are summarized in Table 2. Rainfall intensity and outflow rate were directly measured at all stations. In Maryland, inflow was measured directly. In Greensboro and Louisburg, 100% of rainfall falling directly on the bioretention area was added to calculated runoff generated in the watershed. The SCS curve number method (USDA-SCS 1986) was used in Greensboro with a CN of 98 (100% imperviousness) to determine the volume entering the two cells. Five min rainfall data were used to determine peak inflow intensities and times. As was found by Pitt et al. (1999) asphalt surfaces transmit nearly all rainfall to runoff; thus, in Louisburg, an initial abstraction of 2.0 mm (0.08 in.) for impervious surfaces (CN of 98) and 8.4 mm (0.33 in.) for pervious surfaces (CN of 86) were subtracted from rainfall falling on each land use.

In high precipitation or strong intensity events, the CP and SS effluent flow rates occasionally exceeded the weir ranges and are reported as the maximum measurable flow rates with a "larger than" note. Input and output flow rates lower than the flow rate measurement ranges at both sites are reported as no flow. In Greensboro and Louisburg, mixing of bypass flow and underdrain flow was prohibited by placing a top on the monitoring boxes and forcing bypass to be routed to the storm sewer. Similarly, bypass was routed to the storm sewer via a curb-opening inlet at CP and via an elevated slotted drain at SS. In all cases, volume (V_e) was calculated using simple numerical integration of flow rate (Q) measurements over time increments (dt *or* Δt) for the entire runoff duration, t_d

Table 2. Summary of Inflow and Outflow Sampling and Monitoring Equipment Used at Each Bioretention Cell

Site	CP	SS	G1	G2	L1	L2
Duration	April 2006–July 2007	April 2006–July 2007	July 2003–September 2004	July 2003–September 2004	June 2004–December 2004	June 2004–December 2004
Rain gauge [mm (in.)]	ISCO 674 0.25 (0.01)	ISCO 674 0.25 (0.01)	Global water 0.25 (0.01)	Global water 0.25 (0.01)	Global water 0.25 (0.01)	Global Water 0.25 (0.01)
Inflow data logger	ISCO 6712FR with 730 bubbler module	ISCO 6712FR with 730 bubbler module	Sigma 900 max	Sigma 900 max	Sigma 900 max	Sigma 900 max
Outflow data logger	ISCO 6712FR with 730 bubbler module	ISCO 6712FR with 730 bubbler module	Infinity data logger	Sigma 900 Max	ISCO 6712 with 730 bubbler module	ISCO 6712 with 730 bubbler module
Inflow	20 cm Tracom cutthroat flume	23 cm Parshall flume	SCS curve number	SCS curve number	Initial abstraction	Initial abstraction
Outflow weir	20 cm Thel-Mar plug in weir	15 cm Thel-Mar plug in weir	30° V notch	60° V notch	30° and 45° V notch	30° and 45° V notch
Surface ponding	NA[a]	NA[a]	NA[a]	NA[a]	Infinity data logger	Infinity data logger

[a]NA=not available.

$$V_e = \int_0^{t_d} Q(t)dt = \sum_{t=0}^{t_d} Q(t)\Delta t \quad (1)$$

Water Balance Methods Specific to Louisburg

In Louisburg, water level in the ponding zone was monitored using an Infinity data logger placed in a 10 cm (4 in.) well with screening only above the soil surface. Water level data collected every 10 min were only used to verify when bypass occurred, and were not used to calculate flow rates over the bypass devices. When there was no inflow occurring, the drop in water level measured by the data logger was used to determine infiltration rate. Bypass for L1 was calculated by subtracting infiltration and surface storage volumes from inflow. Infiltration was summed at the observed infiltration rate of 2.5–3.8 cm/h (1.0–1.5 in./h) from the start of rainfall until the end of bypass. (Bypass was assumed to have ceased when the surface ponding level had drawn down to the height of the bypass structure invert.) The surface storage volume was obtained from an as-built survey of the cells. For Cell L2, bypass was calculated by subtracting underdrain flow from inflow for those events with ponded levels above the bypass structure. The water balance equation applied to these cells was

$$Q_i = \mathrm{ET} + Q_u + \mathrm{EXF} + \Delta S + \mathrm{bypass} \quad (2)$$

where Q_i=inflow volume; ET=evapotranspiration volume; Q_u=outflow volume from the underdrain; EXF=exfiltration volume to groundwater; and ΔS=change in storage.

Six 10 cm (4 in.) auger holes were drilled approximately 1.8 m (6 ft) deep along the outside and inside of the bioretention fill soil of both Louisburg cells to verify that no water was leaving or entering through the impermeable membrane in L2. At the time of inspection, about 24 h after a 13 mm (0.5 in.) rainfall event in March 2005, the lined cell was saturated within the soil media and unsaturated outside the media. The unlined cell was wet but not saturated inside the fill soil and moister outside the media along the perimeter of the fill zone. This provided evidence that water did not penetrate the liner, that the media of L1 was drained rapidly, and suggested that water was exfiltrating the unlined cell.

Data Handling and Statistical Analyses

Discrete rainfall events were defined if separated with a dry period greater than 6 h. Probability plots for hydrologic parameters were created by ranking the measured values. The plotting position for each value on the probability scale p was calculated from

$$p = \frac{i - 3/8}{(n + 1/4)} \quad (3)$$

where i=ith smallest number among a sample size n (Cunnane 1978). Data were plotted on a log scale and often described by a straight line (with some deviation at the extremes), implying their log-normal distribution nature, which has been previously used for approximation of storm water parameters (Van Buren et al. 1997; Flint and Davis 2007).

Results and Discussion

Monitored Storm Events Characterization

To examine the representative nature of the rainfall distribution, events for this study were compared to Kreeb's (2003) study of rainfall duration and frequency for 10,352 storm events at 15 weather stations within the state of Maryland. The bioretention hydrologic monitoring events at CP and SS had similar profiles in rainfall depth and duration with typical Maryland storms except for a greater occurrence for the 0.255–0.635 cm rainfall depth and a lower chance for large events (>2.54 cm; no monitored event falls in this category) at CP. Overall, the monitored storms closely resemble the distribution of rainfall depth and storm durations in Maryland and appear to be representative.

A similar study was conducted by Bean (2005) for nine cities in North Carolina, including Greensboro and Raleigh–Durham. The latter is the closest airport to Louisburg (approximately 45 km). Bean (2005) calculated the likelihood of a given event size assuming a rain event occurred. In Greensboro, of the 46 events monitored, 24 of them exceeded the median (10.0 mm), indicating that a relatively normal precipitation period was monitored. In Louisburg, the sampling period was relatively wetter. Of

Table 3. Precipitation Characterization from Six Bioretention Cell Sites

	Number of events		Precipitation depth (cm)		Precipitation duration (h)		Influent loading (m^3/m^2)	
Cell	Total	With outflow	Range	Median value	Range	Median value	Range	Median value
CP	22	16	0.03–2.05	0.47	0.1–24.9	4.6	0.003–0.683	0.058
SS	60	28	0.03–5.82	1.13	0.03–32.3	5.8	0.0–1.09	0.122
G1	63	23	0.25–12.47	0.76	0.33–36.7	5.1	0.0007–2.64	0.021
G2	63	41	0.25–12.47	0.76	0.33–36.7	5.1	0.0007–2.64	0.021
L1	27	24	0.18–5.84	1.36	0.53–26.3	7.1	0.003–0.529	0.061
L2	27	26	0.18–5.84	1.36	0.53–26.3	7.1	0.002–0.476	0.047

the 34 events monitored, 20 of them exceeded the median event (9.7 mm). Many of the events were relatively large in Louisburg, as 15% of all events exceeded the 90% storm (10% expected). The largest event of the study, 12.47 cm, occurred in Greensboro.

Hydrologic Benefits

The variety of rainfall characteristics can be exemplified with data from all six cells (Table 3). The number of events examined ranged from 22 to 63. Median precipitation amounts ranged from 0.47 (CP) to 1.36 cm (L1 and L2), with several storms exceeding 5.5 cm occurring in both states. The median event duration ranged from 4.6 h (CP) to 7.1 h (L1 and L2). The minimum lengths were well under 1 h, while the maximum storm duration exceeded 1 day at all six cells, with G1 and G2 having one storm lasting more than 36 h. Several events, particularly at CP, SS, G1, and G2, generated runoff from the drainage areas, but no measurable underdrain effluent was detected, indicating that the entire runoff volume was stored by the soil and lost through exfiltratration and evapotranspiration. The net pollutant discharge of these events was therefore zero.

In Maryland and Greensboro a few monitored events were impacted by wintry precipitation. In one event at CP, three at SS, and three at G1 and G2, a wintry mix occurred in which the precipitation could not be registered on the rain gauge and only the Maryland runoff flow rates were recorded. The wintry mix events in Greensboro did produce underdrain flow; however, they were excluded from all analyses because inflows were not measurable.

Fig. 1 illustrates typical hydrographs for CP and SS. Both cells delayed and reduced the runoff peak flows, and diminished the runoff volume through infiltration. In many events, however, more complicated hydrologic conditions occurred, such as multiple flow peaks, varying rainfall intensity and event durations, and overlapping runoff events. An example of a two-peak rainfall event and bioretention cell response is shown in Fig. 2 for G1 and G2. The first portion of the storm is entirely mitigated by G1, but not G2. However, the second storm peak produces outflow from both cells.

Figs. 3 and 4 demonstrate the rainfall depth as a function of event duration for the SS and G2 cells. The trend lines drawn for the "zero discharge" events approximately serve as the boundary between the flow and no-flow events. For example, in SS the intercept and slope of the line are 0.31 cm and 0.044 cm/h, implying that SS can treat a rainfall $\leq$0.31 cm ("cell storage depth") or with an intensity $\leq$0.044 cm/h ("cell storage intensity") in its drainage area without discharge. The other cells showed similar trends, albeit with different specific values among the flow cat-

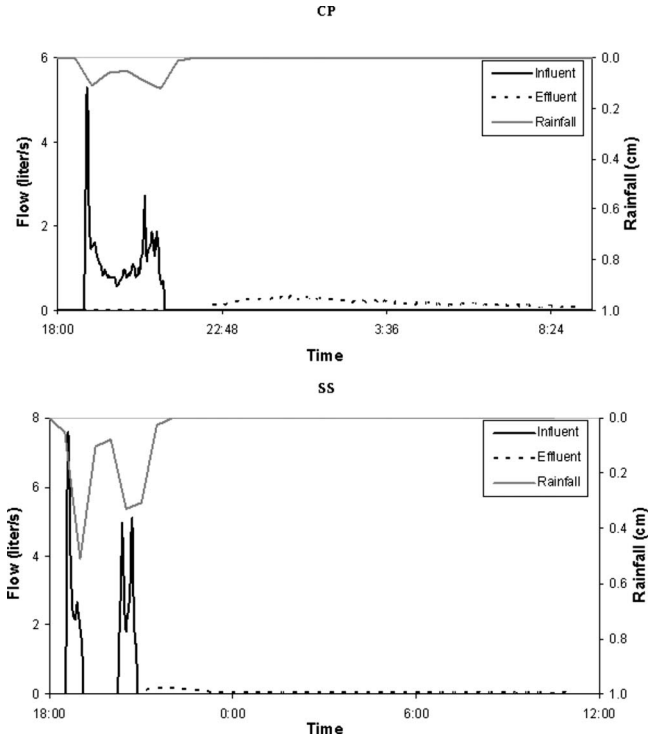

Fig. 1. Hydrographs of CP and SS for event on April 3, 2006

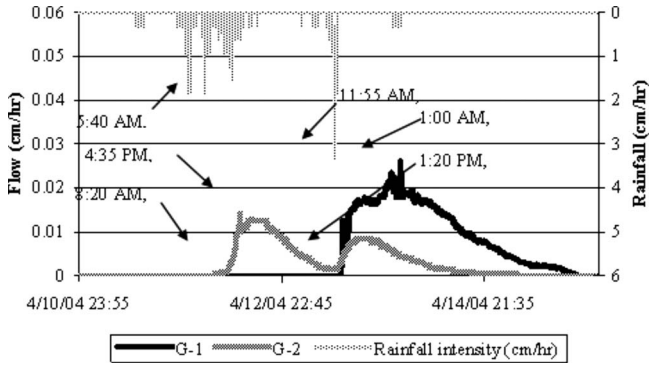

Fig. 2. Rainfall and underdrain flow intensity for both cells in Greensboro (April 2004)

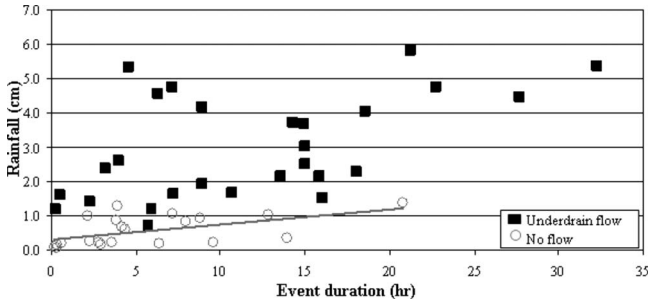

Fig. 3. Rainfall depth and event duration for SS events with and without generating underdrain flow. Trend line represents rainfall-duration relationship for no-flow events.

egories. For all cells, the storage depths and intensities ranged from 0.06 to 0.46 cm and 0.003 to 0.08 cm/h, respectively (Table 4). At the North Carolina sites, discharge with bypass occurred at rainfall depth ranging from 1.67 to 5.26 cm. No bypass was noted at the CP and SS sites, probably because of the lower rainfall recorded at CP and the deep (30 cm) ponding depth at SS.

Davis (2008) proposed three metrics for describing the restoration of hydrologic conditions by bioretention facilities: the peak flow rate ratio of effluent to influent R_{peak}, the peak discharge time span ratio of effluent to influent R_{delay}, and the effluent/influent volume ratio f_V, which are defined as

$$R_{peak} = \frac{q_{peak\text{-}out}}{q_{peak\text{-}in}} \tag{4}$$

$$R_{delay} = \frac{t_{q\text{-}peak\text{-}out}}{t_{q\text{-}peak\text{-}in}} \tag{5}$$

$$f_{v24} = \frac{V_{out\text{-}24}}{V_{in}} \tag{6}$$

where $q_{peak\text{-}out}$ and $q_{peak\text{-}in}$ represent the peak flow rates of the effluent and influent; $t_{q\text{-}peak\text{-}out}$ and $t_{q\text{-}peak\text{-}in}$ represent the time elapsed between the beginning of influent flow and the peak effluent and influent flows; V_{in}=input storm water runoff volume to a bioretention cell; and $V_{out\text{-}24}$=corresponding outflow volume leaving the cell within 24 h. Through providing buffer capacity for runoff surges with opportunity for infiltration, a successful bioretention facility can affect a drainage area to simulate the

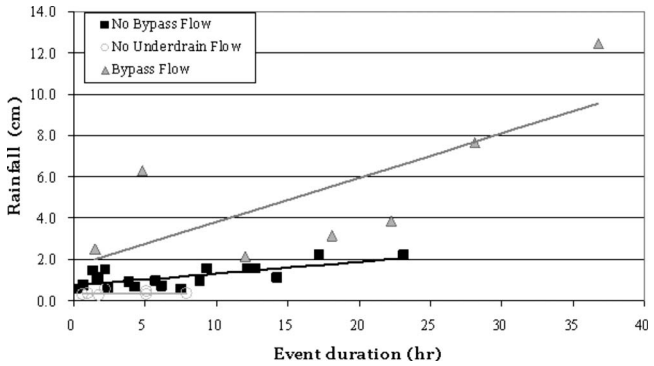

Fig. 4. Rainfall depth and event duration for G2 events with and without generating underdrain flow, and with/without bypass flow

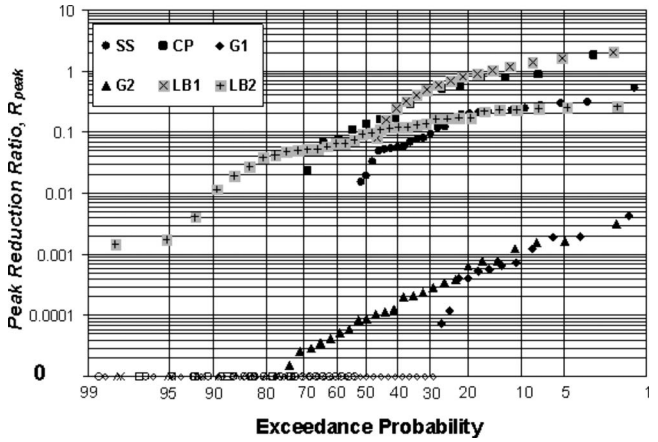

Fig. 5. Runoff peak reduction ratios for all six bioretention cells

predevelopment hydrology and reduce R_{peak} and f_v, while correspondingly increasing R_{delay}.

Results of these metrics for all sites are presented in Figs. 5–7. For the events in which no output flow was observed, a R_{delay} value of 200 was used, since values range from 1 to 180. Comparisons among the cell performances, literature, and target values are presented in Table 5. All measurable events had peak reduction ($R_{peak}<1$), with median R_{peak} values of 0.14 (CP), 0.10 (L2), 0.04 (L1), 0.02 (SS), and <0.01 (G1 and G2). The predicted exceedance probability for the cells to achieve the target R_{peak} value (<0.33), (Davis 2008) is 70% (CP), >90% (SS, L1, L2), and >99% (G1 and G2). Other bioretention studies have noted that the exceedance probabilities for lined field bioretention facilities to meet this target value is 30–42%, and median R_{peak} values of 0.15 (UNHSC 2006) and 0.40–0.48 (lined), (Davis 2008) have been reported.

The median R_{delay} values ranged from 200 (SS and G1) to 4 and 3 (L1 and L2, respectively). Over 70% of events are predicted to meet the R_{delay} target (>6), (Davis 2008) for three cells (70% at CP, 75% at G1, and >80% at SS). The three other North Carolina sites were somewhat less effective (60% at G2, 45% at L1, and 25% at L2), but comparable to 31–38% for other field bioretention facilities (Davis 2008).

The median f_{V24} values are 0.6 (CP and L2), 0.36 (L1), and <0.1 (SS, G1, and G2). Approximately 40% (CP and L1) and 75–82% (SS, G1, and G2) of the events are expected to achieve the f_{V24} target (<0.33), (Davis 2008). The compliance value of f_{V24} for L2 was relatively low (15%), due to its shallow depth and impermeable liner. Literature f_{V24} values for bioretention are 0.18–0.23 (median values, also lined), and the probability to meet the target value is expected to be 55–62% (Davis 2008). The

Table 4. Summary of Treatable Storms for All Six Bioretention Areas

Bioretention cell	Rainfall storage depth (cm)	Rainfall storage intensity (cm/h)	Bypass min depth (cm)	Bypass min intensity (cm/h)
CP	0.06	0.016	NA[a]	NA[a]
SS	0.31	0.044	NA[a]	NA[a]
L1	0.30	0.007	3.20	0.040
L2	0.20	NA[a]	5.26	0.006
G1	0.46	0.080	1.67	0.214
G2	0.35	0.003	1.67	0.214

[a]NA=Not available.

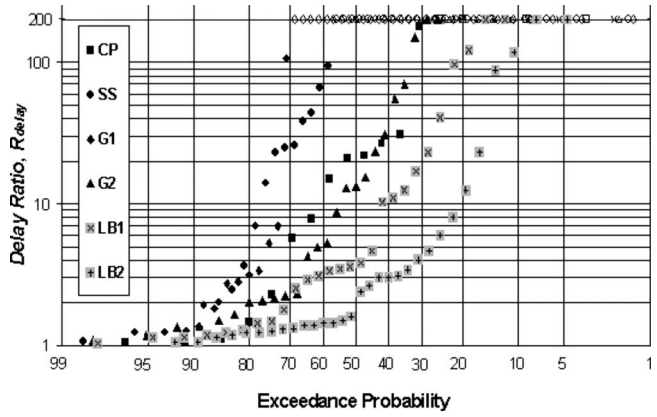

Fig. 6. Runoff peak delay ratios for all six bioretention cells. Events with no outflow are plotted at $R_{delay}=200$.

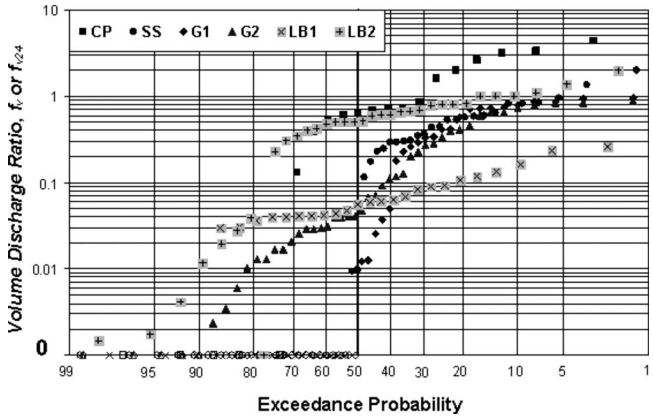

Fig. 7. Runoff peak volume ratios for all six bioretention cells

events with effluent volume > runoff volume ($f_{V24}>1$) are assumed to have been caused by groundwater surge from the nearby creek or other cells during intense or long-duration rainfall events, particularly at CP.

Impact of ET

Per the field confirmation, EXF and ΔS were assumed to be zero for the lined cell (L2) and ET was calculated as the difference between input and output flow using the entire Louisburg data set

$$ET_2 = Q_{i2} - Q_{u2} \quad (7)$$

where ET_2=evapotranspiration loss calculated at cell L2; Q_{i2} =inflow volume to cell L2; and Q_{u2}=volume of outflow from L2. It is assumed that the two Louisburg cells experienced similar ET rates (the cells were planted with the same vegetation types at the same density). Therefore, exfiltration from the unlined cell (L1) corresponds to the difference between input and output flow, subtracted by the ET from L2

$$EXF_1 = Q_{i1} - Q_{u1} - ET_2 \quad (8)$$

where EXF_1=exfiltration loss from cell L1; Q_{i1}=inflow volume; Q_{u1}=outflow volume measured at the outlet; and ET_2 is calculated in Eq. (7). L2 reduced runoff volume by 19% over the course of the study, which is attributed entirely to ET. L1 lost a total of 27% of inflow to ET and exfiltration over the entire study period, with the 8% difference attributed to exfiltration. The soils at the Louisburg site are relatively clayey, which coupled with a relatively shallow media depth of L1 and L2 and their general situation at the bottom of a bowl should explain the relatively small amount of observed exfiltration loss. The high hydraulic conductivity, excessive pore space given the soil type, and small volume of soil contained within the 0.5–0.6 m deep media produced short retention time for water, rapidly passing through the media to the underdrains. Little time was permitted for ET or exfiltration, as illustrated in Table 5 and Fig. 6, where Cells L1 and L2 had the smallest impact on R_{delay}. However, due to the rapid infiltration, the cells treated a large portion of total study period runoff (77% for L1 and 89% for L2, Table 6), resulting in high pollutant reduction rates (Hunt et al. 2006). This indicates that a balance between filtered water volume (and therefore treated for pollutant removal) vis-à-vis residence time may be an important design consideration.

The total volumes and proportions of inflow for each component of the water balance for the Louisburg cells are summarized in Table 6. The volume of runoff entering and the bypass volume leaving L1 were greater than those of L2. The total difference in inflow between the two cells was nearly equal to the difference in bypass. Consequently, the total amount of water entering the soil media (non-bypass) of the two cells was nearly equal.

Table 5. Comparison of R_{peak}, R_{delay}, and f_{V24} among All Bioretention Cells, Target Values, and Literature Values

Metrics	R_{peak}		R_{delay}		f_{V24}	
Target value[a]	<0.33		≥6		<0.33	
	Expected probability of achieving target (%)	Median value	Expected probability of achieving target (%)	Median value	Expected probability of achieving target (%)	Median value
Cell CP	70	0.14	70	22	40	0.60
Cell SS	>90	0.02	>80	200	75	<0.10
Cell G1	>99	<0.01	75	200	80	<0.01
Cell G2	>99	<0.01	60	13	82	<0.10
Cell L1	>90	0.04	45	4	44	0.36
Cell L2	>90	0.10	25	3	15	0.60
Davis (2008)	30–42	0.40–0.48	31–38	—	55–62	0.18–0.23
UNHSC (2006)	—	0.15	—	—	—	—

[a]Davis (2008).

Table 6. Water Balance for Louisburg Cells over Monitoring Period (June 15–December 2004)

Period totals	Cell L1 (mm)	Percent of inflow (%)	Cell L2 (lined) (mm)	Percent of inflow (%)
Inflow	581	100	499	100
Underdrain Flow	290	50	350	70
Bypass	135	23	56	11
Total Out[a]	425	73	406	81
ET[b]	108	19	93	19
EXF[b]	48	8	0	0
Entering soil media	447	77	443	89

[a]Sum of underdrain flow and bypass.

[b]Calculated based on equations in methods assuming $\%ET_1 = \%ET_2$.

Hydrologic Impact of ISZ

G1 contained an ISZ, while G2 did not. Since both cells were otherwise similar, this allowed for a comparison of the hydrologic impact of the ISZ. Figs. 2 and 8 provide illustrative examples of these two cells' response to June 2004 and July 2004 events. Fig. 8 illustrates the draw down rate of soil water level within G1, and given a soil porosity, corresponds to the volume of water that either exfiltrated or evapotranspired. It took approximately 8 days for G1 to empty free soil water from the bottom of the cell. This provided enough volume to capture the July 27 rainfall event in entirety, resulting in no outflow.

The difference in peak flow delay between the cells is attributed to the volume of storage within the ISZ. During the first of two back-to-back events (separated by approximately 36 h) on April 11, 2004 (total rainfall 3.15 cm), and April 13 (total rainfall 1.57 cm), the cell with the ISZ was able to store and nearly fill (Fig. 2). Because the G1 ISZ needed to fill for outflow to occur, no outflow was measured during this event. The time needed to fill the storage zone was equal to the delay in commencement of outflow between the two cells. When water reached the bottom of the media column within the G2 conventional cell it was immediately able to leave through the underdrains. The outflow lag time corresponded to the time it took water to percolate through the media to the underdrain. G1 was not completely drained during the intervening 1.5 day dry period, reducing the total potential storage volume. So, when the subsequent storm arrived on April 13, cell G1 performed not as a 1.2 m deep cell but as one with somewhat less media storage depth. This difference is supported by the increased probability and higher median value of R_{delay} for G1, as compared to G2 (Table 5). Little difference between the cells was noted when examining R_{peak} and f_{V24}.

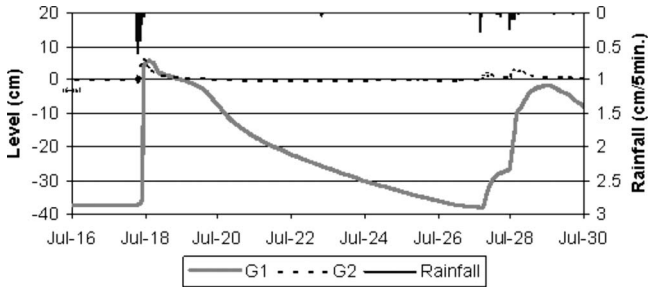

Fig. 8. Level of water in weir boxes at outlet of two cells in Greensboro during July 2004. Level of zero corresponds to invert of weir. No flow is observed until level rises above invert.

Factors Affecting Bioretention Hydrologic Performance at Maryland Sites

Linear regression analyses using the least squares method were attempted to determine correlations between storm event characteristics [rainfall depth, rainfall duration, rainfall intensity, average daily temperature, and antecedent dry weather period (ADWP) for the constant monitoring events at SS] and the bioretention hydrologic performance (in terms of f_{V24} and R_{peak}; R_{delay} was not used because it contains arbitrarily assigned values). Average daily temperature data were obtained from the Maryland State Climatologist Office (MSCO 2007) for the Maryland and District of Columbia metropolitan area.

The results of the regression analyses indicate that both f_{V24} and R_{peak} may be a function of the rainfall depth; R_{peak} may be dependent on the rainfall duration (all with a coefficient of determination $R^2 > 0.41$) (Fig. 9). The average daily temperature, rainfall intensity, and ADWP did not appear to affect f_{V24} and R_{peak}, nor did the rainfall intensity affect f_{V24} (all with a $R^2 < 0.15$). The results show that lower rainfall depth and duration favored effluent peak and volume reduction at both Maryland facilities.

Performance and Design

Evaluation of six facilities allows some investigation of design and performance correlation. However, as is clear from Table 1, the designs of all six facilities were different. This is one of the current drawbacks with widespread implementation of bioretention; that is the design varies jurisdictionally. Inspecting Table 1, a number of important design parameters vary, including media depth and characteristics, as well as the area ratios. Nonetheless, every bioretention facility provided hydrologic benefits by slowing and reducing runoff flow, which assist in providing flood control, reducing channel erosion, and promoting groundwater recharge. SS, G1, and G2 demonstrated better performance in nearly all metrics compared to CP, L1, and L2 and in terms of managing inflow without discharge. When contrasting the two Maryland cells, although SS has a lower cell surface area to drainage area ratio (2%) than CP (6%), and handled a higher hydraulic loading ($0-1.09\ m^3/m^2$, median $=0.122\ m^3/m^2$ or 12,400 L) compared to CP ($0.003-0.683\ m^3/m^2$, median $=0.058\ m^3/m^2$ or 10,400 L) during the observation period, it still demonstrated better hydrologic performance. It is believed that the greater media depth of SS (0.9 m) provides larger runoff storage capacity than that of CP (0.5–0.8 m). Similarly, the two better performing cells with respect to volume reduction, peak mitigation, and peak delay in North Carolina (G1 and G2) were nearly twice as deep as L1 and L2. The extra media volume appears to be an important design metric.

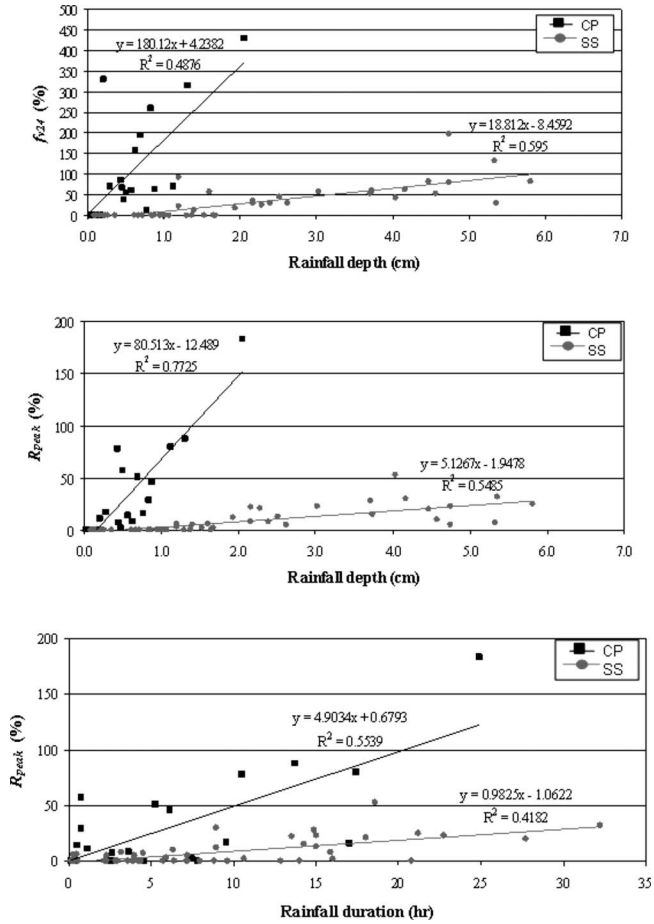

Fig. 9. Regression analyses of f_{V24} and R_{peak} as function of rainfall depth, and R_{peak} as function of rainfall duration

SS was also designed with a greater ponding depth (0.30 m, compared to 0.15 m of CP) to handle higher hydraulic loadings and to overcome infiltration resistance from the thicker media. Finally, CP media is sandy loam while SS media is sandy clay loam. The higher clay content in SS (20%) compared to CP (7%) presumably renders SS media with a lower hydraulic conductivity (which was not measured). As such, the effluent flow rates (normalized to the cell areas) in SS are lower than those of CP, resulting in longer runoff hydraulic retention time (which also favors runoff pollutant removal).

With the hypothesis that media depth is the most important factor controlling hydrologic performance, it is noted from Tables 1 and 5 that SS, G1, and G2 are the deepest cells and have the three lowest median values for R_{peak} and f_{V24}; as well, the two highest values for R_{delay} are among this deep group. Fig. 10 shows the relationships for R_{peak} and f_{V24} as a function of depth for the six cells. Obviously, it is premature to declare a dependence, but the trends are consistent with what may be expected and the linear r^2 values for the six points are fairly large (0.54 and 0.76 for R_{peak} and f_{V24}, respectively). These relationships deserve further exploration, but clearly suggest that deeper media provide greater hydrologic benefit in terms of flow peak and volume reduction. Nonetheless, higher ponding storage and cell volume also imply higher construction cost; a deep media design may also be inappropriate at areas with elevated groundwater level and shallow storm water drainage infrastructure.

The importance of unrestricted exfiltration (that is, the absence of an impermeable liner) also appears to be an important design feature. In most cases CP, SS, G1, G2, and L1 exhibited better hydrologic performance compared with L2 (Table 5) and with two lined bioretention cells from prior studies (Davis 2008). The hydrologic performance of the lined cells is believed to be limited because their infiltration function is restricted by the liner (Sharkey 2006; Davis 2008). As such, infiltration function is considered to be of critical importance for bioretention design.

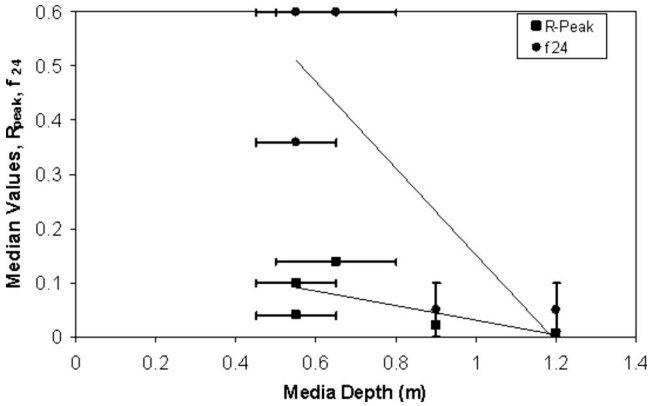

Fig. 10. Median values of R_{peak} (Fig. 5) and f_{V24} (Fig. 7) as functions of media depth for all six bioretention cells. Three cells have variable depth, which is shown with error bars. Lines are linear best fit to data, suggesting lower values for R_{peak} and f_{V24} with increasing media depth.

Conclusions

Several conclusions are derived from this research as follows:

1. Bioretention is capable of mitigating postdevelopment hydrology caused by impervious surfaces. By delaying and reducing runoff peak flows, reducing outflow (runoff) volumes, and promoting infiltration, these hydrologic improvements can assist in flood control and channel erosion protection from urbanization, as well as promote groundwater recharge.
2. Bioretention exhibits excellent hydrologic performance for small rain events, but performance becomes reduced under more extreme precipitation events. A larger media volume: drainage area ratio and greater media depth can enhance the performance in large events.
3. Deeper media depths (>0.9 m, like G1, G2, and SS) appear to promote more infiltration and ET than shallower media depths such as those of CP, L1, and L2. While more costly, deeper, or larger volumes of media can more closely approach the LID goal of replicating predevelopment or a target hydrologic performance. Media depth may be a controlling design parameter for hydrologic management.
4. While brownfield infill development, runoff hotspots, or structural concerns may necessitate a liner, the cell lined with an impermeable membrane exhibited the poorest hydrologic performance.
5. The incorporation of an internal storage zone (G1) did not have a discernable impact on outflow hydrographs for medium to large events. The impact was, however, pronounced for small storms, many of which were completely captured and either exfiltrated or evapotranspired. Only 37% of events produced outflow from G1. With its paired cell, G2, which has no ISZ, approximately 65% of storms produced outflow.

6. The amount of ET was estimated to be rather substantial (19%), even from shallow media cells. This demonstrates a major goal of LID: replication of predevelopment hydrology.

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