Field Performance of Bioretention: Hydrology Impacts

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Abstract: Flows into and out of two bioretention facilities constructed on the University of Maryland campus were monitored for nearly 2 years, covering 49 runoff events. The two parallel cells capture and treat stormwater runoff from a 0.24 ha section of an asphalt surface parking lot. The primary objective of this work was to quantify the reduction of hydrologic volume and flow peaks and delay in peak timing via bioretention. Overall, results indicate that bioretention can be effective for minimizing hydrologic impacts of development on surrounding water resources. Eighteen percent of the monitored events were small enough so that the bioretention media captured the entire inflow volume and no outflow was observed. Underdrain flow continued for many hours at very low flow rates. Mean peak reductions of 49 and 58% were noted for the two cells. Flow peaks were significantly delayed as well, usually by a factor of 2 or more. Using simple parameters to compare volume, peak flow, and peak delay to values expected for undeveloped lands, it was found that probabilities for bioretention Cell A to meet or exceed volume, peak flow, and peak delay hydrologic performance criteria were 55, 30, and 38%, respectively. The probabilities were 62, 42, and 31%, respectively, for Cell B.

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Introduction

Urban development, roadways, and associated infrastructure now cover a significant fraction of U.S. land. Stormwater runoff from urbanized land is a leading cause of impairment to lakes and estuaries in the United States (USEPA 1996). Continued development of land and "sprawl" is a major environmental concern in many areas, such as the Chesapeake Bay watershed. This spread of development is identified by the propagation of hard, continuous, impervious surfaces such as roads, sidewalks, parking lots, and building roofs throughout the watershed. These surfaces are unable to absorb, store, and attenuate stormwater as do natural forested lands. Increases in impervious surfaces in a watershed generally increase stormwater runoff volumes, associated peak flows, and the pollutant loads and concentrations that the event transports; runoff times of concentration are decreased. Alterations to stream ecology have been noted in areas that are as low as a few percent impervious, and once the impervious fraction reaches 10–30%, major declines are found in habitat and water quality indicators (e.g., Wang et al. 2001).

Low impact development (LID) is an environmental philosophy that includes a focus on controlling urban rainfall and stormwater runoff at the source. The goal is to manage site design and construction so that the hydrology and water quality of a developed site approximate that of the initial undeveloped land. The LID approach acts to minimize grading, disconnect impervious areas, preserve the existing landscape and topography, increase flow lengths, and lengthen the concentration time for stormwater runoff. LID best management practice (BMP) technologies are vegetated on-site infiltration-based techniques that are receiving increased attention for the management of stormwater and runoff from developed areas. Bioretention, also known as rain gardens, is a prominent LID technology that has been installed in many areas and continues to draw increasing interest.

Structurally, bioretention facilities consist of approximately 0.7–1.0 m of a porous media, composed of a sand/soil/organic matter mixture. This media layer is covered with a thin (2.5–8 cm) layer of standard hardwood mulch (e.g., PGCo 2001). Various grasses, shrubs, and small trees are established to promote evapotranspiration, maintain soil porosity, encourage biological activity, and possibly promote uptake of pollutants. A healthy stand of vegetation is also important to the aesthetics of the bioretention facility. Stormwater runoff is directed into the facility, allowed to pool, and infiltrates through the plant/mulch/soil environment (Fig. 1). Water can pond on the surface, typically up to 15 cm, above which a manhole or swale diverts the overflow water away from the site. Ponded water eventually drains through the system or evapotranspires, with a goal of drainage in 4–6 h to prevent long-standing water.

Little quantitative information on hydrologic impacts of LID and bioretention is available. Several LID/infiltration modeling exercises have indicated that increasing the amount of infiltration areas in a developed tract can reduce hydrologic impacts for small rainfall events. Effects on large storm events, however, are predicted to be minimal (Holman-Dodds et al. 2003; Brander et al. 2004; Williams and Wise 2006). Antecedent moisture conditions greatly affect the efficacy of infiltration practices. The incorporation of bioretention/infiltration practices was indicated to be beneficial in replicating predevelopment hydrology.

Several recent studies have examined stormwater runoff flows through infiltration systems similar to bioretention. Barber et al. (2003) tested a pilot-scale physical model and completed a mathematical modeling investigation of an ecology ditch, noting reductions in peak flows and delays in flow peaks. Similarly, Sansalone and Teng (2004, 2005) collected field data and com-

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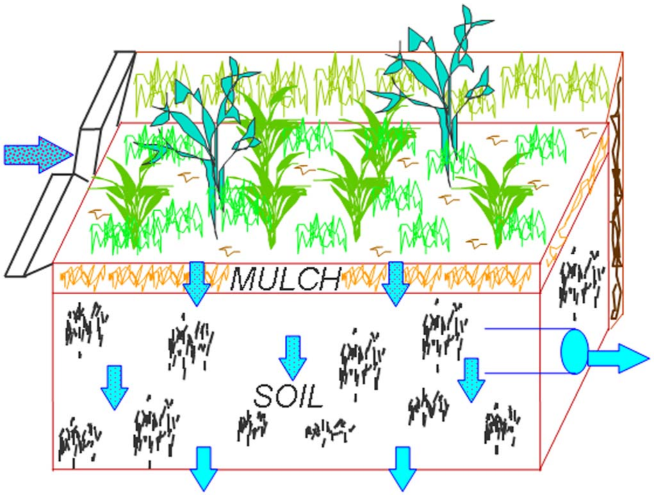
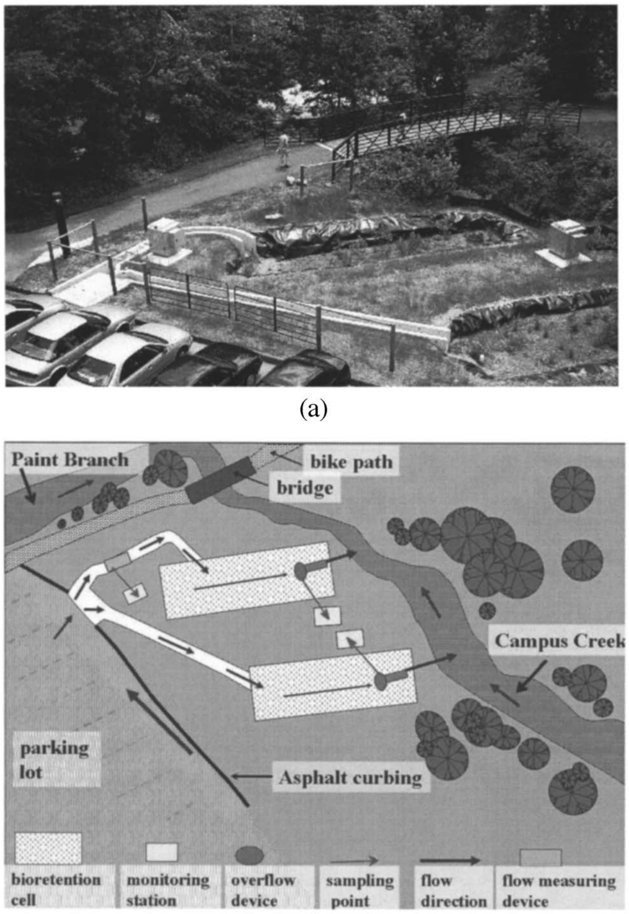


Fig. 1. Diagram of bioretention/rain garden

pleted flow modeling through a partial exfiltration reactor (PER). Again, improvements in hydrologic parameters were noted. The greatest impact was noted for the smallest events; high antecedent water contents were detrimental to performance.

Full-scale hydrologic performance information for bioretention, however, is sparse. Dietz and Clausen (2005) noted reductions and delays in flow peaks at their field rain garden sites, but details were not provided. To address this deficiency, a project was initiated to construct two bioretention facilities on the University of Maryland campus. Hydrology and water quality were measured at the bioretention facilities for nearly 2 years. The focus of this paper is on quantifying the reduction of hydrologic flow peaks and volume, along with delays in peak timing via bioretention. A related objective is to define LID hydrologic goals for bioretention performance and to evaluate the University of Maryland facilities based on these goals.



(a)

(b)

Fig. 2. University of Maryland, College Park bioretention site diagram. Top panel: aerial photograph. Bottom panel: stormwater runoff flow path. Photo by Rebecca C. Stack. (Davis 2007, with permission of Mary Ann Liebert, Inc. Publishers.)

Site Description

A bioretention research and education site was constructed on the University of Maryland campus (College Park, Md.) in Fall 2002/Spring 2003. The site contains two parallel bioretention cells that capture and treat stormwater runoff from an approximately 0.24 ha section of an asphalt surface parking lot. An asphalt curb was constructed along the perimeter of the parking lot to funnel sheet flow to the corner of the lot where the facilities were located (Fig. 2). The parking area is high use, employed year-round for commuter students and athletic events. Each bioretention cell is rectangular, width of 2.4 m, length of 11 m. The resulting bioretention surface area is about 28 m^2 for each cell, producing a drainage:bioretention area ratio of about 45.

One of the bioretention cells (the *shallow cell, B*) was constructed according to the standard bioretention design outlined in The Bioretention Manual (PGCo 2001). In addition to the standard media, the second cell incorporates an experimental anoxic zone at the bottom to encourage denitrification of runoff that passes through the cell (the *deep cell, A*). Laboratory studies have demonstrated that such anoxic zones, seeded with shredded newspapers, can be effective in promoting denitrification of infiltrating water (Kim et al. 2003).

The standard media in each cell consists of an engineered soil mix of 50% (by volume) construction sand, 30% topsoil, and 20% compost, with a clay content of less than 10%, based on current design recommendations (PGCo 2001). The total media depth in each cell is 0.9 m (Cell B, without anoxic sump) and 1.2 m (Cell A, with sump), respectively. Small gravel was packed around the underdrain system that was also wrapped in a nonwoven geotextile to prevent clogging in the perforated pipe. Each cell was covered with approximately 8 cm of rough shredded hardwood mulch (PGCo 2001). In the deep cell, the anaerobic zone was filled with a sand and newspaper mix using an approximate ratio of 17 g newspaper per kg of sand, approximating the ratio used by Kim et al. (2003).

Vegetation was selected from the Bioretention Design Manual (PGCo 2001) list, based on local nursery availability. Preference was given to shrubs and herbaceous plants that were observed to be successful in local existing bioretention facilities. Plantings were identical between cells both in location and species composition with one notable exception. A zinc hyperaccumulator, *Thlaspi* sp. (Angle et al. 2003), was included at the input end of Cell A, but none survived a few weeks beyond their initial planting.

Both cells were lined with a polypropylene liner for research purposes to minimize migration of water into or out of the system. (A liner is not recommended for normal bioretention applications.) A 15 cm perforated plastic pipe runs the length of each cell, below the media, to collect and convey infiltrated water to Campus Creek, a small first order stream that runs through the University of Maryland campus.

Monitoring Methodology and Data Handling

The parking lot flow enters a concrete splitter box where the flow is equally divided to the two bioretention facilities. One stream passes through a 15 cm Tracom parshall flume for flow measurement and water quality sampling. The flows then enter the two cells. The cell underdrains are directed to a manhole, where outfalls are outfitted with two 30.5 cm Thel-Mar plug-in weirs for flow measurement. Bubble flow meters (ISCO 4230/3230) were positioned at each flow measurement device to record inflow and outflow rates throughout the duration of a runoff event.

Stormwater monitoring began in the summer of 2003 and concluded in the winter of 2005. Runoff volumes, V_e, were calculated based on simple numerical integration of flow measurements over time

$$V_e = \int_0^{t_f} Q(t)dt \tag{1}$$

and compared with cumulative volumes given by flow meter outputs once every 4 h.

Probability plots for hydrologic parameters were created by ranking the observed values from largest to smallest. The plotting position for each value on the probability scale, p, was determined as

$$p = \frac{i - \alpha}{(n + 1 - 2\alpha)} \tag{2}$$

where i=ranking number and n=total number of observations. For a normal distribution, a value of $\alpha = 3/8$ is employed (Cunnane 1978; Harter 1984). Data were plotted on a log scale and usually were adequately described via a straight line, albeit with some deviation at the extremes, suggesting that the data are approximately log-normally distributed, which is a common approximation used for hydrologic data (Van Buren et al. 1997).

Results and Discussion

Because of the system design, system overflow events could not be separated from normal bioretention infiltration performance. Overflow events, based on evidence of debris deposits on the manhole covers, were estimated to have occurred during approximately 15% of the storms recorded. This should account for some of the variability in the recorded flow performance.

Typical hydrographs for the bioretention pair are presented in Fig. 3. The inflow is represented per cell and corresponds to the temporal stormwater runoff flow from the parking lot directed into each of the bioretention facilities. Outflows A and B signify the respective bioretention undrain flow responses. In this particular event, two large inflow peaks are noted, about 7 h apart. The hydrologic benefits of the bioretention facilities are clearly illustrated by the delay of approximately 2 h before the detection of effluent flow and the diminished, delayed peaks. Similar results are noted for other rainfall events. All events, however, were not this simple. In many cases, runoff events were complex, with several peaks resulting from increases and lulls in rainfall intensity. As to be discussed, small effluent flows continued from the bioretention cells for several days, occasionally overlapping the next inflow runoff event. This made quantifying the hydrologic impact of the bioretention facilities more complex.

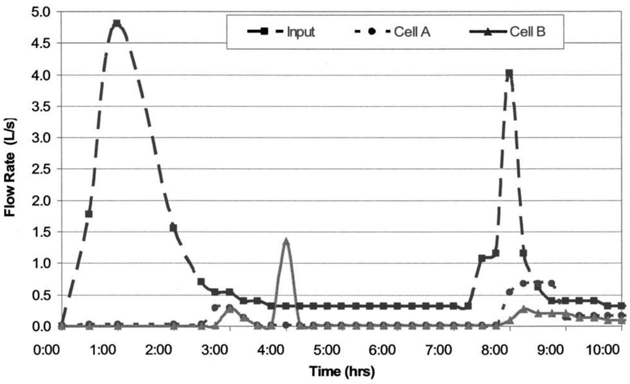


Fig. 3. Input and output hydrographs for University of Maryland bioretention facilities

In all, 49 runoff events were monitored, with 41 having all data for both bioretention cells. In the other 8 events, data from one of the cells was lost due to failure of the flow meter, a dead battery, or a clogged weir. A range of over two orders of magnitude of total runoff volume to each cell is recorded in the data set, from 0.044 to 8.1 m^3/m^2 (volume of input runoff per bioretention cell area, equivalent to applied water depth to the cell). The mean event was 1.6 m^3/m^2; the median event was 0.81 m^3/m^2 with the 10th and 90th percentile events at 0.11 and 4.0 m^3/m^2, respectively.

The range of runoff volumes, combined with other meteorological and hydrologic factors, such as antecedent moisture conditions and flows, created bioretention responses that, taken as a composite data set, could be considered effective in hydrologic management, but some individual events produced atypical results. In eight of the smallest events, no measurable flow left the bioretention cells, indicating that the entire water volume was attenuated within the media. Therefore, no flow peak resulted and the corresponding discharge pollutant load is zero. Fig. 4 shows the total input runoff volume as a function of duration for 34 events with duration less than 30 h. The line drawn on this plot

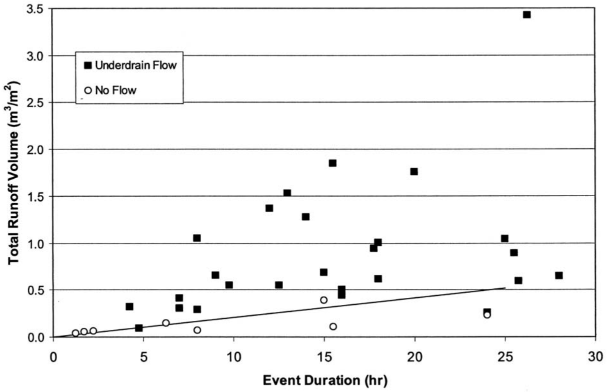


Fig. 4. Total input runoff volume and event duration, demonstrating events that produced no underdrain flows in the bioretention cells. The line approximates the division between the flow/no flow events. The slope of this line corresponds to an average runoff flow rate that can be completely managed by the bioretention cells.

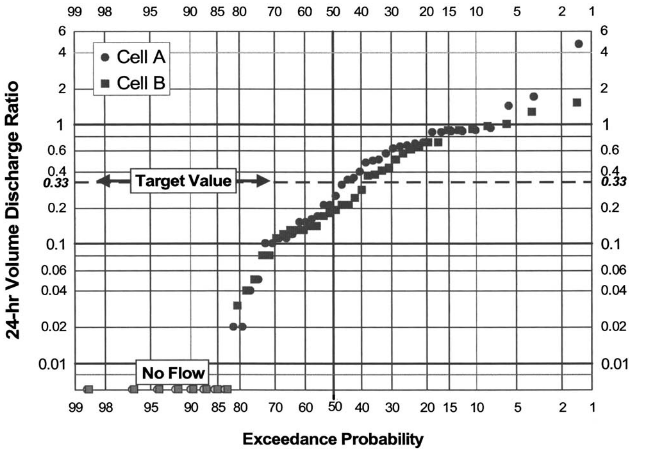


Fig. 5. Probability plot for 24 h volume discharge ratio [Eq. (3)] for University of Maryland bioretention facilities

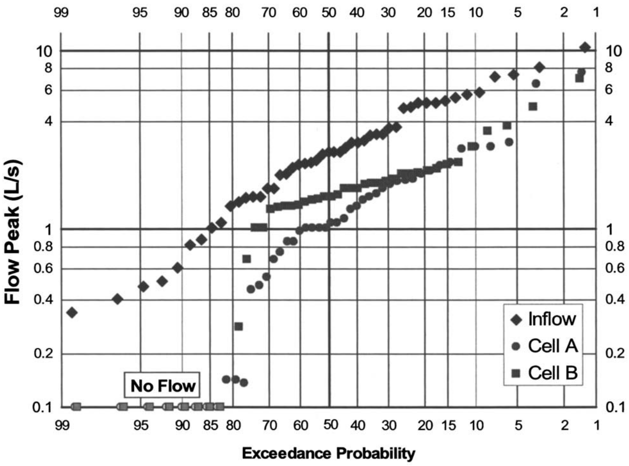


Fig. 6. Probability plot for input and output peak flow at the University of Maryland bioretention facilities

approximates the division between the flow/no flow events. The slope of this line corresponds to an average runoff flow rate that can be completely managed by the bioretention cells and is equal to 0.021 $m^3/h/m^2$, or 2.1 cm/h. This corresponds to a rainfall intensity of about 0.052 cm/h over the parking lot drainage area, assuming a rational method $c=0.9$. Because the liner severely limits exfiltration into surrounding soils, performance without the liner may be expected to be better, especially in areas with relatively permeable native soils.

Bioretention storage and holdup of stormwater runoff is a key performance metric. It was noted during this study that flows continued from the underdrains of both bioretention facilities for many hours, and frequently, for several days at very low flow rates. Because of the practical challenges of measuring low flows for extended times, an outflow volume is defined after 24 h of flow. The fraction of input water measured leaving each system after 24 h, f_{V24}, is defined as

$$f_{V24}=\frac{V_{\text{out-24}}}{V_{\text{in}}} \tag{3}$$

where V_{in}=input stormwater runoff volume (L) to one cell and $V_{\text{out-24}}$=corresponding volume (L) of outflow from one cell after 24 h.

A probability plot based on Eq. (2) for f_{V24} is given in Fig. 5. As discussed earlier, eight events were small enough so that the bioretention media captured the entire inflow volume and no outflow was observed, producing $f_{V24}=0$. To maintain the probability distribution, these eight events were included (plotted arbitrarily at 0.006 in Fig. 5). Median values for f_{V24} were 23% for Cell A and 18% for Cell B, indicating approximately 1/4 to 1/6 of the input volume being released in 24 h; the mean values were 48 and 35%, respectively, overall demonstrating that the bioretention facilities were very effective in managing runoff volume. In 3 events for each cell, the f_{24} was greater than the influent volume. This was typically found when the media was saturated from a preceding event or when several waves of flow occurred in the same event.

One of the primary goals of LID is to maintain the predevelopment hydrology of a drainage area. McCuen (2003) recommends three hydrologic metrics to evaluate the efficacy of smart growth strategies, specifically, (1) hydrologic storage compensation; (2) stream channel preservation; and (3) travel time maintenance. Using these metrics as a guide, three hydrologic parameters ware quantitatively evaluated in this study as measures of successful LID performance for the University of Maryland bioretention facilities. As a first simple measure of establishing LID efficacy, a target volume (24 h) of 33% of the influent was established. This value is derived simply from comparing the rational method c coefficient for undeveloped land (0.3) to that of a highly impervious area ($c=0.9$). From the sampling data population, this target was met for 54% of the events for Cell A and 61% of the events for Cell B. The probability plots of Fig. 5 give essentially identical values of 55 and 62%, respectively.

No simple hydrologic variable could predict the 24 h volume attenuation performance of the cells. However, the f_{V24} values were highly correlated between the two cells, with a linear regression forced through the origin giving a slope of 0.91 and a correlation coefficient of 0.83 (data not shown). Several processes are concurrently at work controlling the volume attenuation. For very small events, most of the water is held by and within the media, producing f_{V24} that is small or zero. Yet, for large events, the flow volume is frequently spread beyond 24 h at a low output flow, so again a small f_{V24} will result. Regardless of the attenuation mechanism, the low values found for f_{V24} demonstrate the efficacy of the bioretention media in managing the water volume, although predictively quantifying the effect is somewhat complex.

A second parameter important for quantifying the hydrologic impact of a stormwater management practice is the peak reduction. Reducing peak flow will reduce erosion, scour, and sediment transport in the receiving stream. A probability plot for the recorded flow peaks is given in Fig. 6. Peak flows entering the facilities ranged from 0.34 to 10.5 L/s (0.012 to 0.38 $L/s/m^2$). The highest peak flows exiting the two bioretention cells were 7.6 and 7.0 L/s, respectively, for the deep and shallow cells. The distribution of peak flows clearly shows the reduction resulting from conveying the flow though the bioretention media (Fig. 6). Median and mean values for peak inflow were 2.7 and 3.1 L/s. Median outflows were 1.0 and 1.5 L/s for the bioretention cells, reductions of 63 and 44%, respectively, for Cells A and B. Peak flow exceeded 2 L/s about 67% of the time for the inflow, but only about 26% of the time for the bioretention discharges.

Maximum outflow peaks were compared to their respective maximum inflow peaks during each runoff event using the ratio

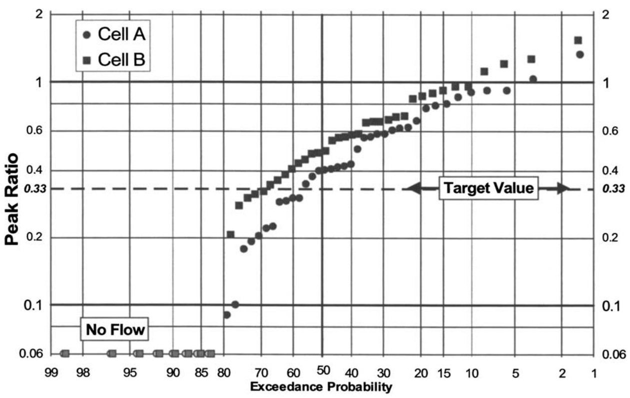


Fig. 7. Peak flow ratios [Eq. (4)] for University of Maryland bioretention facilities

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

where $q_{\text{peak-in}}$=peak inflow (L/s) and $q_{\text{peak-out}}$=corresponding peak outflow. The distribution of data for this ratio for the two cells is shown in Fig. 7. The mean and median output peak ratios are 42 and 40%, respectively, for Cell A, and 51 and 48% for Cell B. In comparison, recent results from a field bioretention study at the New Hampshire Stormwater Center have indicated an average peak flow reduction of 85% (R_{peak}=0.15, UNHSC 2006). Peak flow reductions were also noted in a rain garden study by Dietz and Clausen (2005). Peak flow reductions from a PER utilizing Fe-coated sand ranged from 36 to 85% (Sansalone and Teng 2004). The 33% greater (0.3 m) depth in Cell A, due to the anoxic sump, appears to provide hydrologic benefit by reducing the flow peak to a greater extent than that of the standard bioretention system design.

Considering effluent peak reduction efficiency, as with volume, the LID target is again based on a ratio of rational formula *c* values, yielding a performance target value of 0.33. For Cells A and B, this LID criterion was met in 25 and 43% of monitored events, respectively, including all of the output no-flow events. Similarly, based on the probability distributions of Fig. 7, this criterion can be expected to be met about 30 and 42% of the time.

The final hydrologic performance metric evaluated was flow peak delay. The peak delay ratio, R_{delay}, is defined as the elapsed time to peak for the output flow, $t_{q\text{-peak-out}}$, based on the *input* runoff start time, and the time to peak flow for the input, $t_{q\text{-peak-in}}$

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

By delaying the peak, the hydrologic response through the bioretention facility more closely mimics that of undeveloped land, where natural meandering, infiltration, and vegetation slow the flow. The peak delay ratio data are presented in Fig. 8.

In seven events from Cell A and three events from Cell B, the peak from the bioretention cell discharge appeared before the inflow peak. Although this seems counterintuitive to the bioretention/LID process, this phenomenon nearly always corresponded to a complex storm event with multiple peaks, so that the largest inflow peak may not necessarily correspond to the largest outflow peak. Nonetheless, reductions in peak flow were noted for all of these "early" peaks. The incongruity between the timing of the input and output flow peaks also complicates the hydrologic performance evaluation of the bioretention facilities.

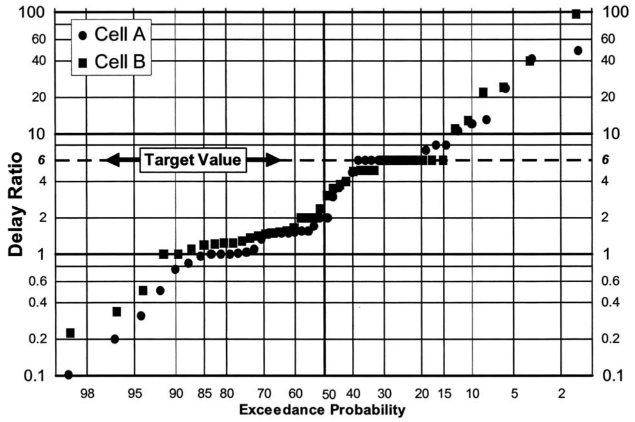


Fig. 8. Peak delay ratios for University of Maryland Bioretention facilities [Eq. (5)]. Events with no effluent flow were assigned a value of 6.

A simple expression for sheet flow time of concentration, T_c, is given by (Davis and McCuen 2005)

$$T_c = \frac{0.938}{i^{0.4}}\left(\frac{nL}{\sqrt{S}}\right)^{0.6} \tag{6}$$

where n=Manning's roughness coefficient; L=flow length; i=rainfall intensity; and S=drainage area slope. For a simple assessment of meeting LID criteria, the T_c of a paved drainage area ($n \approx 0.02$) is compared to that of a light underbrush forest ($n \approx 0.4$), the latter assumed representative of undeveloped land. With the other parameters of Eq. (6) remaining unchanged, the time of concentration ratio for undeveloped to developed land is approximately equal to $(0.4/0.02)^{0.6}$, which is equal to 6. Thus, this value is set as the LID target for the bioretention delay ratio calculated using Eq. (5).

For the events in which no output flow was observed, a value for the timing delay is necessary. As the target value for LID is 6, these events were arbitrarily assigned a value of 6 so that they can be included in the data set. The mean delay ratio was 5.8 for Cell A, with the median delay equal to 2.0, indicating a peak that arrived two times later than that of the influent peak. The same values for Cell B were 7.2 and 2.7, demonstrating an even longer delay. In this case, Cell B, without the sump, provided better performance on the hydrologic parameter, although the reason for this is not clear. For comparison, an average center-of-mass delay of 615 min was reported for the bioretention facility at New Hampshire (UNHSC 2006).

The LID objective of $R_{\text{delay}} \geq 6$ was met in 39% of the monitored events for Cell A and 32% of the events for Cell B. These results are not significantly different from the probability analysis presented in Fig. 8; the LID timing objective can be expected to be met 38% of the time for Cell A and 31% of the time for cell B. Overall, peak delays can be expected for 75–88% of rainfall events.

Two-dimensional modeling of the PER by Sansalone and Teng (2005) support these field bioretention studies of delays in peak flow and volume attenuation. In their study, the hydraulic conductivity of the surrounding soils was evaluated as a variable. In cases where the surrounding soils were very clayey, little water was able to exfiltrate from the PER. This is similar to the bioretention cells of this study that were lined with polypropylene. Overall, the simulations performed by Sansalone and Teng (2005) found that the hydraulic conductivity of the surrounding soil had little impact on the hydrologic performance of the PER. Effective reductions in flow peaks (R_{peak} range of about 0.66–0.14) and peak delays were noted, mostly independent of the flow that was exfiltrated. Field monitoring data demonstrated stormwater volume reductions that ranged from 55 to 70% through exfiltration to surrounding clayey glacial till soils in Cincinnati (Sansalone and Teng 2004, 2005).

Barber et al. (2003) used both a physical and computer model to evaluate the hydrologic performance of an ecology ditch under various rainfall/runoff simulations. The ecology ditch is an infiltration BMP containing compost, sand, and gravel. The peak flow was reduced by a factor of 70% to about 58%, decreasing with storm size. Similarly, peak delay ranged from about 60 to 15 min. A weak relationship was found between antecedent conditions and hydrologic performance effects for large storms. For small events, however, minor changes in the initial water content produced significant effects in hydrologic function; as much as 30% decrease in percent peak reduction and peak delay were seen for as little as 1% increase in prestorm water content. This effect was only discernible for rainfall events less than 1.54 cm.

Drainage area hydrologic modeling exercises produce results consistent with the behavior observed in this study at the individual bioretention cell level. When LID infiltration practices were incorporated on a basin-wide scale, Holmann-Dodds et al. (2003) found runoff behavior equivalent to predevelopment conditions for rain events below 6 cm of total rainfall depth. In these simulations, the hydrologic benefit of the LID practices over traditional pond-based stormwater management practices diminished for larger and less frequent storms. Brander et al. (2004) found that including infiltration practices such as rain gardens in a developed area reduced runoff, albeit not to predevelopment conditions. Greater runoff reduction was noted for smaller rainfall events. Soil type played a major role in infiltration efficacy, with high infiltration rate sandy texture soils demonstrating better performance than low infiltration rate clayey soils.

Summary and Conclusions

Overall, the results of this work indicate that bioretention can be an effective technology for reducing hydrologic impacts of development on surrounding water resources. From a data set of 49 rainfall events, 18% percent of the events were small enough so that the bioretention media captured the entire inflow volume and no outflow was observed. When flow did occur from the facility underdrain, it continued for many hours, and frequently, for several days at very low rates. Typical flow peak reductions of 44–63% were noted (depending on cell depth and statistical parameter used). Flow peaks were significantly delayed as well, usually by a factor of 2 or more.

LID goals were established employing hydrologic parameters expected for undeveloped lands. These targets corresponded to 24 h volume and peak flow reductions of at least 33% and peak delays of at least a factor of 6. Based on collected data, the probabilities of flow through Cell A meeting the LID goals for 24 h volume, peak flow, and peak delay were 55, 30, and 38%, respectively. The probabilities were 62, 42, and 31%, respectively, for Cell B.

Overall, from a hydrologic perspective, the bioretention facilities were successful in minimizing the hydrologic impact of the impervious surface and major reductions can be expected for about 1/3 to 1/2 of the rainfall events. These values may be conservative due to the presence of the liners surrounding the media in the cells.

Acknowledgments

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