Improving bioretention/biofiltration performance with restorative maintenance

Robert A. Brown and William F. Hunt

ABSTRACT

One of the most popular Stormwater Control Measures is bioretention, or biofiltration. Anecdotal evidence suggests that well-designed bioretention cells are often not adequately installed and that maintenance is lacking, leading to less-than-adequate water storage volume and/or surface infiltration rates post-construction. In March 2009, two sets of bioretention cells were repaired by excavating the top 75 mm of fill media, increasing the bioretention surface storage volume by nearly 90% and the infiltration rate by up to a factor of 10. Overflow volume decreased from 35 and 37% in the pre-repair state for two different sets of cells, respectively, to 11 and 12%. Nearly all effluent pollutant loads exiting the post-repair cells were lower than their pre-repair conditions. The bioretention systems employed two different media depths (0.6 and 0.9 m). The deeper media cells discharged less outflow volume than the shallower cells, with 10–11% more runoff volume leaving as exfiltration from the 0.9-m than from the 0.6-m media depth cells. This study showed that maintenance is both critical and beneficial to restore otherwise poorly performing bioretention. Moreover, while deeper media cells did outperform the shallower systems, the improvement in this case was somewhat modest vis-à-vis additional construction costs.

Key words | bioretention, construction, LID, maintenance, media depth, runoff, stormwater, SUDS, WSUD

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INTRODUCTION

Stormwater management is important to mitigate flooding, reduce in-stream erosion pressure, limit nutrient loads in estuaries, and ameliorate stream benthic health (Abal *et al.* 2001; Bledsoe & Watson 2001; Walsh *et al.* 2005; Wheeler *et al.* 2005). If Stormwater Control Measures (SCMs) could mitigate the release of outflow from the smallest and most frequent events in urban catchments, the number of events with runoff and magnitude of flow rates will more closely resemble the pre-developed condition. In turn, managing runoff volume directly decreases pollutant loading to surface waters. Such hydrologic mitigation helps maintain and improve stream health in urban areas (Walsh *et al.* 2005).

Infiltration-based SCMs, a key component of Low Impact Development (LID), Water Sensitive Urban Design (WSUD) and Sustainable Urban Drainage Systems (SUDS), are becoming widely used to achieve more stringent stormwater regulations that focus on water quality and meeting pre-development hydrologic conditions. However, infiltrating SCMs are more susceptible to construction or maintenance complications than traditional SCMs (i.e., retention/detention basin), resulting in less than ideal performance. Clogging from fine soil particles associated with unstable catchments has been observed in infiltrating practices such as permeable pavement and bioretention cells (BRCs) (Bean *et al.* 2007; Asleson *et al.* 2009; Fassman & Blackbourn 2010; Brown & Hunt 2011a).

Poor, or outright lack of, construction oversight diminishes bioretention performance. Retention and detention basins are typically designed to store several metres of water. Consequently, if the target water storage depth for a retention basin is off by 0.1 m, only a minor difference (2–3%) in storage volume results. In contrast, if target elevations for a BRC are off by 0.1 m, the storage capacity could be reduced by more than 30% because BRCs are typically designed to store a maximum depth of up to 0.3 m prior to releasing runoff as overflow. As BRCs are designed with shallow ponding depths, minor oversights in construction can lead to substantial underperformance.

Two major issues to ensure proper functionality of BRCs are: (1) maintenance; and (2) qualified construction

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oversight. BRCs from the study presented herein initially lacked both. Brown & Hunt (2011a) examined the performance of clogged and undersized BRCs for one year. The same systems were then re-examined after the clogging layer was removed and the surface storage volume was increased. The purpose of this article is to highlight the improvements in hydrologic performance and pollutant load reduction by restoring the surface infiltration rate and increasing the surface storage volume for two sets of previously clogged and undersized BRCs that had two different media depths (0.6 and 0.9 m).

Site description

The study site was located in the parking lot of a large commercial retail store in Nashville, NC, USA. Construction took place from June 2007 to February 2008, and monitoring began on March 31, 2008. Seven BRCs treated runoff from an asphalt parking lot, with cells configured in parallel. Three cells (0.9-m media depth) were connected to one outlet drain, and the other four cells (0.6-m media depth) were connected to a different outlet drain (Figure 1). Due to backwater constraints, the last cell in each set was not monitored. The design event for these BRCs was 25 mm (NCDENR 2009). The BRCs were conventionally drained (no saturated zone or internal water storage layer, Dietz & Clausen 2006; Blecken *et al.* 2009; Brown & Hunt 2011b) and vegetated with shrubs, perennials, and trees. More detailed site- and catchment-specific information, including reasons for the BRC underperformance, is available in Brown & Hunt (2011a) and in Figure 1 and Table 1.

After several months, it was observed that the BRCs were not functioning properly. The surface storage zone did not drain within 12 h of an event's conclusion, as required by NCDENR (2009). It usually took 48 h or more to drain. Upon closer inspection, it was observed that the BRCs were clogged with granite fines associated with the asphalt parking lot gravel base layer that washed into the cell during construction, despite attempts by the contractor to prevent this from occurring.

In part due to the clogged layer, overflow occurred more frequently than intended. During the pre-repair period, overflow occurred for rainfall events as small as 9 mm. Per design specifications, overflow should not have occurred for any rainfall event less than 25 mm. After surveying the BRCs and their respective drainage areas, it was determined that the actual ponding depth and surface storage area of the BRCs were substantially less than the design specifications. The actual surface storage volume was only 28 and 35% of the design surface storage volume for the 0.6-m and 0.9-m media depth cells, respectively.

On March 11, 2009, the undersized and clogged BRCs were repaired by removing the top 75 mm of the media. In addition, the side slopes were steepened to modestly increase the surface area. The surface storage volume increased by 89% for both sets of cells; however, they remained relatively undersized with respect to the design event (between one-half to two-thirds of the design capacity). After the repair, the brink overflow depth for the BRCs was calculated via land survey to be 17 mm. Monitoring of the repaired BRCs continued through March 24, 2010.

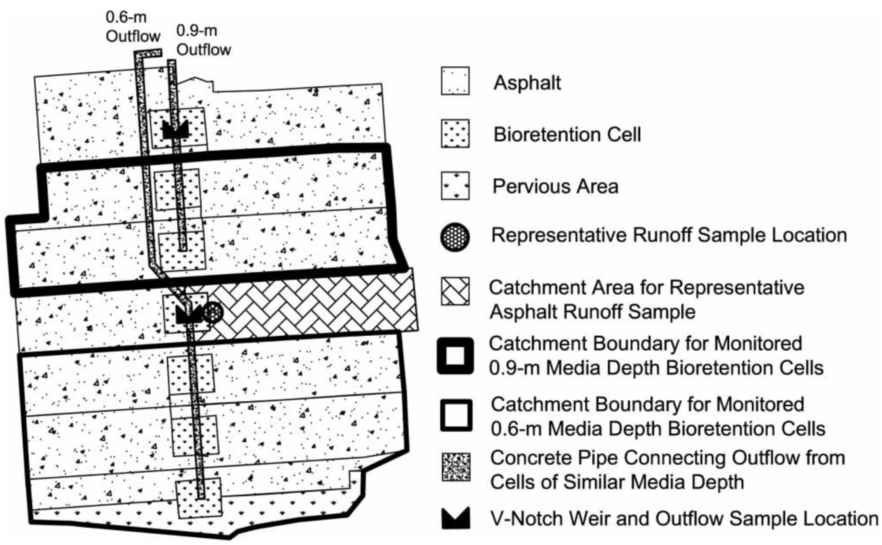

Figure 1 | Layout of catchment and bioretention cells.

Table 1 | Summary of Nashville, NC, bioretention cell characteristics

Design characteristics	0.6-m media depth	0.9-m media depth
Number of cells monitored	3	2
Drainage area	0.68 ha	0.43 ha
Impervious area	83%	97%
Design cell ponding depth	0.3 m	0.3 m
Pre-repair cell ponding depth	0.13 m	0.15 m
Post-repair cell ponding depth	0.2 m	0.27 m
Design cell surface area	425 m^2	300 m^2
Pre-repair cell surface area	290 m^2	206 m^2
Post-repair cell surface area	322 m^2	226 m^2
Drainage area: post-repair cell area	21:1	19:1
Design cell surface storage volume	124 m^3	91 m^3
Pre-repair surface storage volume	35 m^3	32 m^3
Post-repair cell storage volume	66 m^3	60 m^3
Pre-repair storage capacity relative to design	28%	35%
Post-repair storage capacity relative to design	53%	66%
Surface infiltration rate (pre-repair)	2.5–12.7 mm/h	2.5–6.4 mm/h
Surface infiltration rate (post-repair)	10–115 mm/h	11–51 mm/h
K_{Sat} of bioretention media[a]	45 mm/h	
Bioretention media composition[b]	86–89% sand, 8–10% silt, & 3–4% clay	

[a]Determined by constant head permeability test on five, 76 mm (3 in) diameter soil cores taken from the top 0.3 m of the media. Cores were taken from below observed clogging layer.
[b]Determined by hydrometer method (Gee & Bauder 1986).

Field data collection methods

Automated samplers (ISCO 6712™) with integrated bubbler modules (ISCO 730™) and sharp crested weirs were used to measure runoff and outflow rates every minute. A tipping bucket rain gauge (ISCO 674™) and a manual rain gauge were used to measure rainfall intensity and depth, respectively. A 0.75-m wide rectangular weir with end contractions was installed at an inlet curb cut to one of the cells to monitor runoff quality from a representative section of parking lot (Figure 1).

While the weir allowed flow proportional samples to be collected, it did not provide the level of precision desired under low flow rates because of the width of the rectangular weir (0.75-m). Thus, runoff volume was calculated for each event by subtracting an initial abstraction depth from the rainfall depth and multiplying by the drainage area. The specific initial abstraction depths for the different land uses and antecedent moisture conditions are presented in Brown & Hunt (2011a) and were based on results from Pandit & Heck (2009). Outflow (comprised of both drainage and overflow) was measured with a 90° sharp-crested, v-notch weir fixed in each 0.75-m diameter outlet concrete pipe connecting all cells of similar media depth.

Flow-proportional runoff and outflow samples were analyzed for Orthophosphate (Ortho-P), Total Phosphorus (TP), Total Ammonia Nitrogen (TAN), Nitrate-Nitrite Nitrogen (NO_x), Total Kjeldahl Nitrogen (TKN), and Total Suspended Solids (TSS). Organic Nitrogen (ON) was calculated as the difference between TKN and TAN, and Total Nitrogen (TN) was calculated as the sum of TKN and NO_x. Samples were transferred to laboratory containers, placed on ice, and delivered to the NCSU Center for Applied Aquatic Ecology (CAAE) laboratory within 24 h to conduct chemical analyses (U.S. EPA 1983; Eaton *et al.* 1995).

In total, 61 individual hydrologic events were examined during the pre-repair period. After the repair, 75 and 72 hydrologic events were measured for the 0.6-m and 0.9-m cells, respectively. Water quality samples were collected for 18 and 22 paired events for both sets of BRCs, in the pre- and post-repair periods, respectively.

Statistical analysis

Non-parametric statistical tests were used to compare how the different media depths and monitoring periods impacted peak flow rate ratios and 24-h effluent/influent volume ratios between the two monitoring periods (SAS, version 9.1.3). Only paired events were included for (both pre- or post-repair) monitoring, so a Wilcoxon signed-rank test was used. When the pre-repair and post-repair datasets were compared, a Wilcoxon rank-sum test was used. Two-sided tests and a significance level of $\alpha = 0.05$ were used in analyses.

RESULTS AND DISCUSSION

Total annual rainfall for both monitoring periods was within 41 mm of each other. However, slightly larger events were monitored for water quality analysis during the pre-repair period (mean = 31.5 mm, median = 27.4 mm) than during the post-repair period (mean = 25.1 mm, median = 19.6 mm). The largest event recorded occurred during the post-repair period (136.9 mm).

Volume and flow reduction

The distribution of outflow revealed the major improvement attributed to maintaining the BRCs (Figure 2). Substantially less runoff overflowed the post-repair BRCs. Twelve and eleven percent of runoff volume bypassed the 0.6-m and 0.9-m media depth cells, respectively, post-repair. This volume was less than one-third that of pre-repair cells (37 and 35% for the 0.6-m and 0.9-m media cells, respectively). Runoff that bypasses or overflows a BRC essentially receives no treatment, save for a modest amount of sedimentation. By increasing the volume of water that infiltrated the soil media (nearly 90% in the post-repair cells), pollutants in the infiltrated water are exposed to multiple pollutant removal mechanisms (particle filtration, sorption, and biological processes). The increase in runoff entering the media, in lieu of overflowing the system, is attributed to: (1) a larger surface storage volume; and (2) a higher surface infiltration rate (nearly 10 times greater). In terms of outflow reduction, BRCs with deeper media depth (0.9 m) performed significantly better than the shallower systems (0.6 m) during both monitoring periods. These results supported findings of Li *et al.* (2009).

Peak flow rate ratios (R_{peak}) were calculated by the equation (Davis 2008):

$$R_{peak} = \frac{q_{peak\text{-}out}}{q_{peak\text{-}in}} \tag{1}$$

where $q_{peak\text{-}out}$ and $q_{peak\text{-}in}$ represent the peak flow rates of the effluent and influent.

Post-repair outflow (drainage + overflow) was characterized by a higher percentage of drainage, a direct result of having larger surface storage volumes. Because overflow occurred less frequently, peak outflow rates were substantially lower. Additionally, the duration of higher flow rates (>10 L/s/ha) was reduced by a factor of 2 to 3 because the frequency and duration of overflow was reduced. This should minimize the negative impacts that higher flow rates have on receiving streams (Walsh *et al.* 2005). To quantify the impact of increasing the surface storage volume, only events greater than the brink overflow event (9 mm) from the pre-repair period were considered. This subset analysis of only larger events showed that both sets of BRCs had significantly lower peak flow rate ratios (R_{peak}) during the post-repair period (Figure 3). The ability to achieve lower peak flow rate ratios is nearly independent of media depth, but it is strongly dependent on surface storage volume and infiltration potential. Having 'good' surface storage and media infiltration, in essence, diverted a much larger fraction of runoff into the media, which discharges outflow at substantially lower rates. With adequate surface storage volume to minimize occurrence of events with overflow, bioretention has proven extremely effective at reducing peak flow rates for all events other than those that overwhelm the surface storage (Hunt *et al.* 2008; Li *et al.* 2009; Brown & Hunt 2011b). This illustrates the importance of adequately sizing the bowl, or surface storage, volume of BRCs.

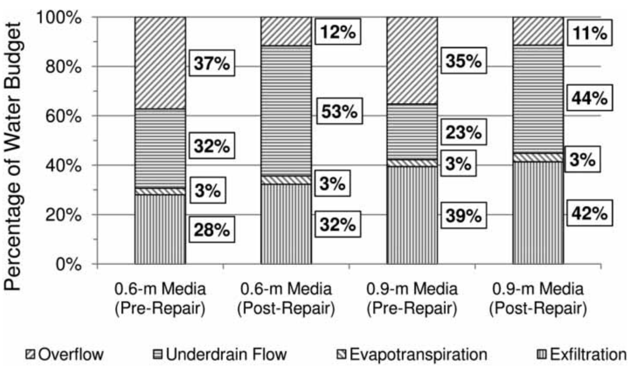

Figure 2 | Partitioning of runoff among overflow, treated underdrain flow, modeled ET, and exfiltration to underlying soil for pre- and post-repair periods.

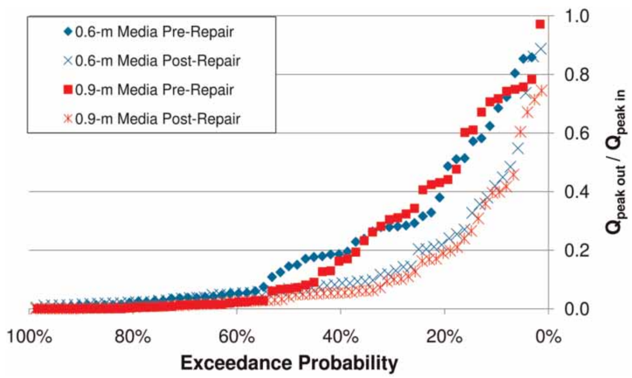

Figure 3 | Peak flow mitigation exceedance probabilities for pre- and post-repair BRCs.

Pollutant load analysis

Pollutant load analyses are presented in Tables 2 and 3 for the 0.6-m and 0.9-m media depths, respectively. In comparing the post-repair period to the pre-repair period, load reductions improved for all pollutants except for Ortho-P for both cells and TP for the 0.9-m media depth cells. The net increase in Ortho-P load explained why TP load reduction was not as substantial in the 0.9-m cells. Pollutant load of Ortho-P was being released two to three times higher than the runoff load. While changes in concentration are not presented herein due to spatial constraints, the influent TP concentrations were relatively low. The average runoff and outflow concentrations were less than one-half of the average TP concentration from eight other parking lots in NC (0.21 mg/L) (Passeport & Hunt 2009). Therefore, it is possible that an irreducible concentration (Strecker *et al.* 2001) of phosphorus may have entered the BRCs, hindering the mass reduction of TP.

CONCLUSIONS AND SUMMARY

This study presented the unique opportunity to study an SCM both before and after a substantial maintenance repair. Two sets of BRCs, differing by media depth (0.6-m and 0.9-m), were constructed in Nashville, NC, USA, as previously described by Brown & Hunt (2011a). They were monitored for one year in a clogged and severely undersized condition. After the year, a maintenance

Table 2 | Pollutant loads for the 0.6 m cells pre- and post-repair periods (pre-repair data first presented by Brown & Hunt 2011a)

	Pre-repair ($n = 18$) Median event size = 27.4 mm			Post-repair ($n = 22$) Median event size = 19.6 mm		
Pollutant	**In (kg/ha)**	**Out (kg/ha)**	**Percent reduction or increase[a]**	**In (kg/ha)**	**Out (kg/ha)**	**Percent reduction or increase[a]**
TKN	2.91	1.78	39	3.44	1.79	48
Org-N	1.75	1.53	13	2.86	1.66	42
TAN	1.16	0.26	78	0.58	0.13	78
NO_x	0.84	1.52	(81)	0.75	0.93	(25)
TN	3.75	3.31	12	4.18	2.72	35
Ortho-P	0.06	0.08	(37)	0.04	0.12	(184)
TP	0.27	0.26	5.3	0.34	0.30	12
TSS[b]	135	39.1	71	204	43.5	79

[a]Parentheses denote an increase in pollutant load.
[b]$n = 21$ for post-repair.

Table 3 | Pollutant loads for the 0.9 m cells pre- and post-repair periods (pre-repair data first presented by Brown & Hunt 2011a)

	Pre-repair ($n = 18$) Median event = 27.4 mm			Post-repair ($n = 22$) Median event = 19.6 mm		
Pollutant	**In (kg/ha)**	**Out (kg/ha)**	**Percent reduction or increase[a]**	**In (kg/ha)**	**Out (kg/ha)**	**Percent reduction or increase[a]**
TKN	3.26	1.37	58	3.65	1.40	62
Org-N	1.90	1.08	43	3.03	1.32	56
TAN	1.36	0.29	79	0.62	0.08	87
NO_x	0.95	2.30	(142)	0.79	1.60	(103)
TN	4.20	3.67	13	4.44	3.00	32
Ortho-P	0.07	0.07	(5.1)	0.05	0.17	(274)
TP	0.30	0.17	44	0.36	0.29	19
TSS[b]	147	23.5	84	213	23.6	89

[a]Parentheses denote an increase in pollutant load.
[b]$n = 20$ for post-repair.

overhaul took place, whereby a restricting fines layer was removed and the overall surface storage volume nearly doubled; the repaired cells were monitored for an additional year. The restorative maintenance reduced the volume of overflow by more than two-thirds, subjecting nearly 90% of the runoff to several bioretention pollutant treatment mechanisms. Consequently, the amount of pollutant reduction provided by the repaired cells was relatively higher than that of the pre-repair cells. When considering only moderate- and larger-sized storm events, peak outflow mitigation was significantly improved after the repair. This was attributed to the larger surface storage volumes and higher surface infiltration rates. A second role of the research was to continue to examine the importance of media depth, which has been highlighted as a key design parameter by Li *et al*. (2009). Increasing the media depth from 0.6 to 0.9 m did increase the volume of exfiltration, as expected, but the magnitude of increase was not substantial (approximately 10–11% of annual runoff volume). Media depth had no noticeable impact on peak outflow mitigation. This study illustrated the importance of installing SCMs correctly and the role of post-installation inspection and maintenance. From an investment standpoint, this study suggested that more care should be taken to provide adequate surface (bowl) storage and consequent construction supervision than to increase media depth beyond 0.6 m.

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