Evaluation of undersized bioretention stormwater control measures for treatment of highway bridge deck runoff

S. K. Luell, W. F. Hunt and R. J. Winston

ABSTRACT

Two grassed bioretention cells were constructed in the easement of a bridge deck in Knightdale, North Carolina, USA, in October, 2009. One was intentionally undersized ('small'), while the other was full sized ('large') per current North Carolina standards. The large and small cells captured runoff from the 25- and 8-mm events, respectively. Both bioretention cells employed average fill media depths of 0.65 m and internal water storage (IWS) zones of 0.6 m. Flow-proportional, composite water quality samples were collected and analyzed for nitrogen species, phosphorus species, and TSS. During 13 months of data collection, the large cell's median effluent concentrations and loads were less than those from the small cell. The small cell's TN and TSS load reductions were 84 and 50%, respectively, of those achieved by the large cell, with both cells significantly reducing TN and TSS. TP loads were not significantly reduced by either cell, likely due to low TP concentrations in the highway runoff which may have approached irreducible levels. Outflow pollutant loads from the large and small cell were not significantly different from one another for any of the examined pollutants. The small cell's relative performance provides support for retrofitting undersized systems in urbanized areas where there is insufficient space available for conventional full-sized stormwater treatment systems.

Key words | bioretention, bridge deck, highway runoff, retrofit, stormwater, undersized

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INTRODUCTION

Bioretention is one of the most popular stormwater control measures (SCMs) in North America and Australasia, for hydrologic and nutrient mitigation. In urbanized areas, space is often too confined to employ full-sized treatment systems able to capture and treat the first 25 mm of runoff. A 25- to 30-mm water quality storm is commonly used worldwide (e.g., Auckland Regional Council 2003; North Carolina NCDENR 2007). As a result, undersized bioretention has the potential for widespread retrofit use. To date, limited research has been performed on intentionally undersized systems. Brown & Hunt's (2011) study addressing the functionality of undersized bioretention cells, which were installed to treat parking lot runoff, suggested that larger cell surface areas increase the likelihood that larger storms will be captured and treated due to a decrease in overflow. Cells with greater fill media depths also generated fewer overflows because of their capacity to infiltrate more water (Li *et al.* 2009; Brown & Hunt 2011). Bioretention cells promote evapotranspiration and exfiltration into surrounding native soils (Li *et al.* 2009) which contributes to small-storm capture, pollutant removal, and long-term hydrologic attenuation (Davis 2008; Hunt *et al.* 2008; Hatt *et al.* 2009; Li *et al.* 2009). Bioretention has proven effective at reducing nitrogen, phosphorous, TSS, and heavy metal concentrations (Dietz & Clausen 2005; Hunt *et al.* 2008; Blecken *et al.* 2009; Passeport *et al.* 2009). A design practice that has become increasingly popular is the inclusion of an internal water storage (IWS) zone, which has been shown to promote nitrate removal, heavy metals removal, and/or exfiltration of stored water through *in situ* soils (Dietz & Clausen 2006; Davis 2008; Blecken *et al.* 2009; Passeport *et al.* 2009). IWS zones are created by fitting underdrain systems with an upturned elbow to form a saturated/anaerobic layer within the bottom of the cell.

Bridges often pass over waterways, allowing their runoff to directly discharge into surface waters below and impact surface water quality. A study in Charlotte, NC, USA, found that TN and TSS loads from a bridge deck were substantially larger than those from two highways in the study (one rural and one urban) due to more frequent highway maintenance

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activities (Wu *et al.* 1998). Similarly, a runoff study from an interstate overpass in Baton Rouge, LA, USA, showed that EMCs of TSS (138 mg/L to 561 mg/L) and COD (128 to 1,440 mg/L) were greater from the bridge than from untreated wastewater in the area (Sansalone *et al.* 2005). Unique issues are associated with the treatment of highway bridge deck runoff, including relatively inaccessible locations and limited surrounding space available for retrofitting full-sized stormwater treatment systems.

The goals of this research were to: (1) examine the impact of fully-sized and undersized bioretention cells on highway bridge deck runoff water quality, and (2) determine the relative performance of the undersized bioretention cell to the full-sized cell from a pollutant removal perspective. If undersized bioretention cells perform 'acceptably well,' then perhaps they could become a well-utilized tool for treating bridge deck runoff and receive a portion of the credit assigned to full-sized bioretention cells.

METHODS

The study site was located in Knightdale, NC, USA, in an easement of two Interstate-540 bridge decks which passed over Mango Creek (35°47′3.4″N, 785°30′48.4″W). The bridge decks were three lanes in both directions, with an associated emergency lane (total width of 18.3 m). The bridge decks had scuppers (i.e., drainage orifices) at approximately 3.4 m intervals along the outside lane. Stormwater was routed from the scuppers for a portion (0.4 ha) of the northbound bridge deck to two bioretention cells – a standard, full-sized cell (hereafter, the 'large' cell) designed to treat the first 25 mm of runoff, and a bioretention cell with half of the standard surface area based upon current NC standards (hereafter, the 'small' cell) (NCDENR 2007). The flow from the northbound lanes was split evenly through a diversion box and discharged to both the large and small bioretention cells.

Both the large and small bioretention cells were designed to have a 23 cm ponding depth, 0.65 m average media depth, and a 0.6 m deep IWS layer which consisted of both media and the entire gravel/drainage layer surrounding the underdrains. The IWS was created by adding an upturned elbow at the outlet end of the two 15 cm diameter high-density polyethylene (HDPE) underdrains located in each cell. The engineered soil media in the cells consisted of 2.9% gravel, 86.8% sand, 7.8% silt, and 2.5% clay (NCDOT 2011) with 3–5% of the total soil mix consisting of pine mulch organic matter to enhance microbial activity. Both bioretention cells were vegetated with centipede grass (*Eremochloa ophiuroides)* sod, as centipede has been planted and survived in bioretention cells in NC. Rock-lined forebays stilled stormwater as it entered the cells (Figure 1(a)). The as-built surface area of the small bioretention cell (101 m^2) was approximately one-half that of the large cell (188 m^2). The large cell captured runoff from the 25-mm event. The bowl storage volume of the small cell (14.0 m^3) was 28% of the bowl storage volume of the large cell (50.8 m^3). As a result, the small cell captured runoff from the 8-mm event – a substantial reduction. Overflow exited each bioretention cell through the cell's outlet structure (Figure 1(b)). Underdrain flow was also conveyed to the outlet structure. The combined flow was conveyed offsite through a 30-cm diameter HDPE pipe.

Rainfall intensity and depth were measured by an ISCO 674™ automatic tipping-bucket rain gauge located on-site. Rain depth was also measured with a manual rain gauge. Storm events were separated by at least a six hour antecedent dry period. Events that were sampled ranged from 4- to 123-mm. During the monitoring period, approximately 1,413 mm of total rainfall fell at the site. Of the total rainfall, 29, 17, 37, and 17% fell in the spring, summer, autumn and winter seasons, respectively, during which 9, 4, 11, and 6 water quality samples, respectively, were collected.

The inlets to both bioretention cells were fitted with a compound weir consisting of a 120° v-notch lower portion (5 cm, invert to top of v-notch) and a rectangular upper

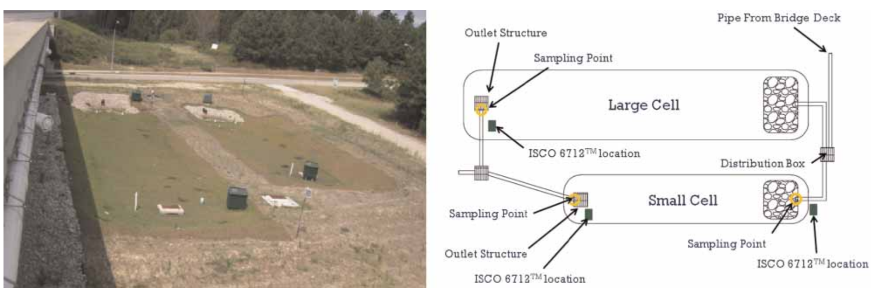

Figure 1 | (a) Standard (left) and undersized (right) bioretention cells at Mango Creek (left image). (b) Bioretention cells schematic (right image).

portion (13 cm, top of v-notch to top of rectangular portion) to take level readings. Weirs were also used to measure outflow from the bioretention cells inside the outlet structures; outflow rates and water quality were measured as the combination of overflow and underdrain flow. ISCO 730™ bubbler modules measured the depth of flow over each weir to calculate flowrate using a derived stage-discharge relationship, which was field verified. Due to frequent unreliable level readings at the bioretention inlet which lead to unreliable recorded inflow data, inflow volumes per storm event were calculated based on rainfall and catchment characteristics using the Initial Abstraction method (Pandit & Heck 2009). During periods of overflow, outflow volumes were set equal to the calculated inflow volumes.

Water quality sampling was undertaken at the inlet to the large bioretention cell and at both bioretention cell outlets (Figure 1(b)) from November 2009 to December 2010. The quality of water entering both cells was considered identical. Flow volumes calculated using the bubbler/weir combination were used by an ISCO 6712™ water quality sampler to take flow-proportional, composite samples at each sampling location. Though the ISCO 6712™-recorded flow data were not accurate enough to be used in hydrologic calculations, the flow-proportional samples that were collected were still considered representative of the water quality throughout the duration of the event. Water quality samples were placed on ice and taken to the lab within 24 h of the end of a rainfall event. Samples were analyzed for total Kjeldahl nitrogen (TKN), nitrate–nitrite nitrogen ($NO_{2,3}$-N), ammonium nitrogen (NH_4-N), total phosphorus (TP) and total suspended solids (TSS) following Standard Methods (APHA/AWWA/WEF 1998). Total nitrogen (TN) concentrations were calculated for each storm event by summing the concentrations of TKN and $NO_{2,3}$-N.

Inflow and outflow water quality were statistically compared using SAS® 9.2 (SAS 2008). Inflow and outflow data were paired ($n = 24$ large cell, $n = 29$ small cell), as were outflow data from the large cell compared to those from the small cell ($n = 23$). The differences between paired data were checked for normality using the Kolmogorov–Smirnov, Carmer-von Mises, and Anderson–Darling goodness-of-fit tests. All statistical tests used a significance level of $\alpha = 0.05$. The Student's t test was used for normally and log-normally distributed data. The Wilcoxon signed rank test was used on non-normally distributed data with only one outlier, while the sign test was used in the case of two or more outliers. Box plots were created using R© software (R 2010).

To calculate pollutant loads, the loads were summed for the total number of storms, and then percent load removals were determined per cell [Equation (1)]. This technique allowed the largest events, and their associated loads, to proportionally influence the result.

$$\%\ \text{load removed} = \frac{(\Sigma\Theta_{in} - \Sigma\Theta_{out})}{\Sigma\Theta_{in}} \times 100 \quad (1)$$

where $\Sigma\Theta_{in}$, sum of per-storm-event pollutant loads at inlet for a given constituent (mg); $\Sigma\Theta_{out}$, sum of per-storm-event pollutant loads at outlet for a given constituent (mg).

RESULTS AND DISCUSSION

Pollutant concentration analysis

Event mean concentration (EMC) data distributions for each sampling point are presented in Figure 2.

In all cases, median effluent concentrations released by the large cell were lower than those released by the small cell. Except for TP in the large and small cell and TKN in the small cell, influent concentrations were significantly reduced by both cells. For TP, the small bioretention cell produced nearly the same median effluent concentration as that of the large cell. However, this may have been due to the near-irreducible influent TP concentration (Strecker et al. 2001). The soil media was tested for presence of phosphorous, which was found to be low. The low influent concentration of TKN may have also had a similar effect on TKN reduction. Further, nitrate-nitrogen was reduced to a greater extent than what is typically seen in traditional bioretention cells with no IWS (Davis et al. 2006; Hunt et al. 2008; Brown & Hunt 2011). This is likely the product of denitrification in the anaerobic bottom portion of the cell. TSS removal was a result of filtration and sedimentation. Differences in effluent concentrations between the large and small cell were significantly different for TKN, $NO_{2,3}$-N, TN, and TP, but not for NH_4-N and TSS.

Effluent concentrations can be used to assess SCM performance and are thought by some to be a more effective means of characterizing SCM efficiency than analyzing fractional removals (Strecker et al. 2001; Li & Davis 2009). McNett et al. (2010) characterized water quality levels by correlating various in-stream pollutant concentrations to benthic macroinvertebrate health and rated them on a scale from 'poor' to 'excellent'. In the Piedmont of North Carolina (the location of this study site), 'good' water quality concentrations for TN and TP are 0.99 mg/L and 0.11 mg/L,

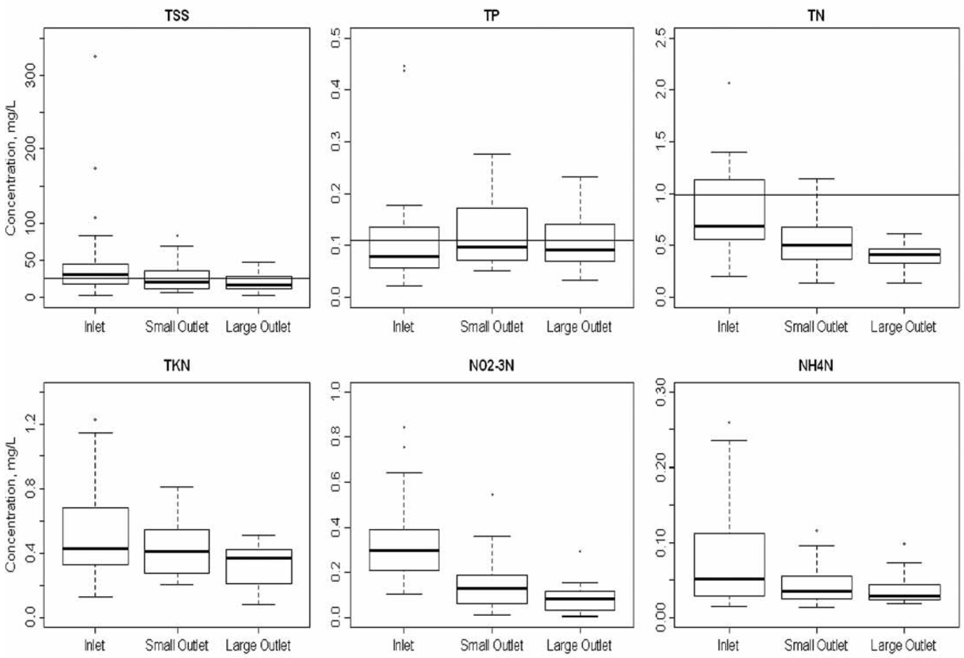

Figure 2 | Box plots of nutrient and TSS concentrations ($n = 24$ inlet to large cell outlet, $n = 29$ inlet to small cell outlet, and $n = 23$ large cell outlet to small cell outlet). Horizontal lines represent target North Carolina water quality standards in the Piedmont region for TSS, TP, and TN.

respectively. 'Good' water quality supported intolerant benthic macroinvertebrates, such as *Ephemeroptera* (mayflies) and *Trichoptera* (caddisflies). Target concentrations for TSS (25 mg/L) were based on that used by Barrett *et al.* 2004. The target values established for TSS, TP, and TN are shown as horizontal lines in Figure 2.

The median TN and TP concentrations of the bridge deck runoff (represented in the box plots as bold horizontal lines) were below the 'good' targets. When analyzing the pollutant concentrations based on this metric, the bioretention cells' inability to reduce the TP concentrations in the runoff was not necessarily a sign of inadequately functioning bioretention cells. Runoff from the bridge deck was quite clean relative to target nutrient concentrations and compared to other bridge deck studies (Wu *et al.* 1998; Sansalone *et al.* 2005; Gan *et al.* 2007). Median effluent concentrations from both bioretention cells were at 'good' to 'excellent' water quality levels (McNett *et al.* 2010) for both TN and TP. Median TSS concentrations were reduced below the target concentration by both cells.

Pollutant load analysis

Pollutant load data are presented in Figure 3 ($n = 19$). Nearly all of the pollutant loads were significantly different between the inlet and the outlet for both bioretention cells; exceptions were TP loads in the large and small cells and TKN loads in the small cell. When comparing effluent loads, no significant difference was found between the large and small cells. However, the median effluent loads from the small cell were higher (though not statistically) than those from the large cell in every case (Figure 3).

The large bioretention cell provided somewhat greater load reduction than the small cell for all pollutants due to greater flow reductions and pollutant removal capabilities. While the small bioretention cell did not treat stormwater to the same extent as the large cell, the results presented suggest that undersized bioretention cells should receive a portion of the pollutant removal credit that appropriately designed and sized bioretention cells receive. Pollutant removal credit is assigned to a particular type of SCM based on what percentage of pollutant load the SCM is generally capable of removing or sequestering (Strecker *et al.* 2001). Currently, in the Piedmont of North Carolina, bioretention cells with IWS layers receive 85, 40, and 45% regulatory credit for TSS, TN, and TP removal, respectively (NCDENR 2007).

Table 1 shows the mean load reductions achieved by the small and large cell. The small cell's TN and TSS load reductions were 84 and 50% that of the large cell's load

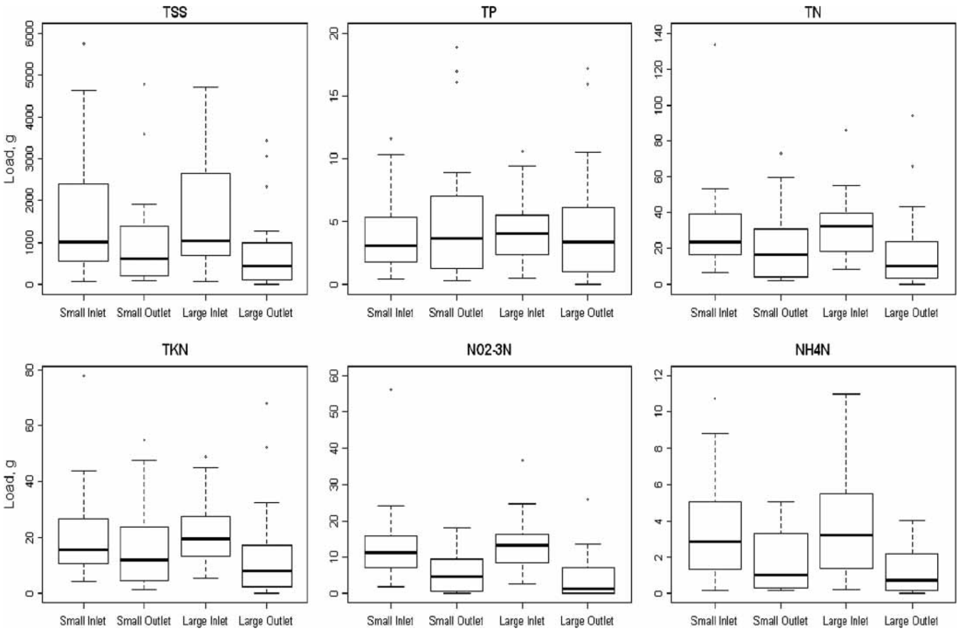

Figure 3 | Box plots of nutrient and TSS loads ($n = 19$).

Table 1 | Percent pollutant load reductions for the bioretention cells at Mango Creek as calculated using summation of loads

Constituent	Sum of influent pollutant loads (kg)	Sum of effluent pollutant loads (kg)	Percent reduction (%)
Small cell (n = 25)			
TKN	0.46	0.34	25.9
$NO_{2,3}$-N	0.30	0.12	58.0
TN	0.71	0.45	37.3
NH_4-N	0.08	0.04	54.1
TP	0.10	0.11	−13.3
TSS	42.8	21.8	49.1
Large cell (n = 21)			
TKN	0.44	0.29	35.0
$NO_{2,3}$-N	0.29	0.09	68.4
TN	0.69	0.38	44.9
NH_4-N	0.08	0.03	68.0
TP	0.10	0.09	4.4
TSS	38.3	16.7	56.4

reductions, respectively. Similar conclusions are not possible for TP because the small cell modestly increased TP loads. The TP load increase was the result of concentration increases in the small cell (Figure 2) attributed to the low initial influent TP concentrations.

CONCLUSIONS

- Bridge deck runoff concentrations for TN and TSS at the Mango Creek site were well below those for other bridge deck runoff studies in the literature. These low influent concentrations had an impact on the pollutant reductions achieved by the bioretention cells; however, TN and TSS influent concentrations were still significantly reduced.
- TP was not significantly reduced in either cell. However, when comparing TP effluent concentrations to target North Carolina water quality standards as determined by benthic macroinvertebrate health, both cells released TP concentrations near the 'good' water quality threshold. TN and TSS concentrations were also reduced beyond their target levels in both cells.
- The large bioretention cell attained lower median effluent nutrient and TSS concentrations than the small bioretention cell for every examined pollutant. Load reductions of all pollutants were also greater (but not significantly so) for the large bioretention cell.
- Though the calculated median pollutant loads showed that the small cell did not reduce loads to the same extent as the large cell, the results suggest that effluent concentrations and loads were somewhat similar between the cells. The percent load reduction metric suggests that it may be reasonable for a bioretention cell undersized by half to be awarded at least 50% of

the removal credits assigned to a fully-sized system. Small cells do provide a benefit and their use should be encouraged in locations with limited available space for retrofits. Long-term performance was not gauged during this study, and it is possible that smaller cells will have a shorter functional life due to limited media for the removal of certain pollutants.

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