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Hydrologic Evaluation of Established Rain Gardens in Lincoln, Nebraska

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Abstract. Increased urbanization has resulted in water quality and flooding problems for many receiving waters in the United States. Rain gardens are one type of best management practice commonly used in low impact development (LID). Many studies have evaluated large engineered bioretention cells in research settings. There is little information on the effectiveness of homeowner-maintained rain gardens that rely on deep percolation as the method for water exfiltration. Repeatable controlled experiments are very rare in hydrologic studies due to the inherent variability of weather data. The objective of this study was to evaluate the hydrologic properties of twelve established rain gardens using a stormwater runoff simulator. A volume-based design storm of 1.2 inches, the “water quality volume” storm, was applied as a synthetic SCS-type II 30-minute runoff hydrograph to each garden based on its respective catchment characteristics. Every rain garden tested drained in 30 h or less, with six gardens draining in less than one hour. Results of the study indicate that these 2-4 year old rain gardens are limited not by infiltration rate, which often met or exceeded performance standards, but rather by inadequate surface storage characteristics. Overall, rain garden storage capacity was poor with only two gardens able to store and infiltrate the water quality volume. On average, rain gardens studied were able to store and infiltrate only 40% of the design storm volume. Focus on accurate construction and berm grading should be a high priority for rain garden installers. Use of a stormwater runoff simulator to assess post-construction performance is feasible and can provide repeatable data on hydrologic effectiveness.

Keywords. Rain garden, stormwater, best management practice, runoff simulator, low impact development
Introduction

Urban stormwater runoff is a major factor contributing to impairment of water bodies in the United States (US EPA, 2004). Conventional urban development involves constructing gutters, storm sewers, and paved channels (Novotny, 2003), causing increased peak flows and decreasing the lag time of runoff hydrographs (Leopold, 1968). This can disrupt the sedimentation and erosion equilibrium of receiving channels, resulting in channel widening and bank failure, causing property damage and loss of habitat for aquatic species (US EPA, 2004). Additionally, in urban development soils are often compacted and the top soil layers stripped away, resulting in higher bulk densities, lower organic content, and less biotic health. These factors can negatively influence the process of infiltration (Novotny, 2003). In 1999, Prince George’s County, Maryland integrated best management practices (BMPs) with policy-making and land planning, thus pioneering the cohesive watershed management technique known as Low-Impact Development (LID). The goal of LID is to return a site or watershed to a pre-development hydrology condition through stormwater volume reduction and pollution prevention measures that compensate for land development (Prince George’s County, 1999).

In the last two decades, LID has been shown to be an effective way to decentralize stormwater management by implementing multiple structural and non-structural controls to improve the ecology of the watershed (Dietz, 2007). Two particularly effective BMPs used to accomplish LID objectives are bioretention and rain gardens. Research on water quality and hydrologic characteristics of larger, more complex bioretention systems has been progressing since 1993 (Clar and Green, 1993). The focus of most studies has been on outflow/inflow comparisons, effluent pollutant concentrations, and percent reductions in pollutant concentrations (Davis et al., 2001; Davis, 2008; Davis et al., 2009; Hunt et al., 2006; Dietz and Clausen, 2005).

While performance knowledge is growing on large-scale bioretention systems that utilize an under drain outflow structure, less research exists on smaller, residential-scale rain garden cells without under drain systems that rely solely on ET and percolation into native soil as the mechanisms for outflow reduction, rather than underdrains. A number of studies on bioretention cells with an under drain use impermeable membranes around the native soil-engineered soil interface to capture all exfiltrate for water quality mass balance purposes (Li and Davis, 2009). In addition, research done on rain gardens that rely more on root zone dynamics from native prairie vegetation rather than heavily engineered soils and drainage systems are lacking.

A number of research studies have been done on bioretention performance considering the climatic and soil conditions of the Eastern United States (Maryland, North Carolina, Connecticut, etc.). However, there is a lack of knowledge on hydrologic performance of rain gardens in arid, semiarid, or humid Midwest climates that have different soil types and native plant species. Although many sites have incorporated bioretention, uncertainty about the implementation and performance still exists in these regions, especially in areas new to the concept of LID and bioretention (Meder, 2009). Locating bioretention systems on privately owned land has been identified as a barrier to their adoption in storm water management plans as it requires oversight of proper installation, use, and maintenance (Morzaria-Luna et al., 2004). Testing of homeowner-maintained rain gardens is scarce in the literature, and may provide a more realistic evaluation of the state of established rain gardens.

Currently, water quality monitoring is the most widely used method to evaluate bioretention and rain gardens (US EPA, 2002). Monitoring of a single BMP is sometimes impractical because of the time required to obtain enough samples to make conclusions, as well as the effort sometimes required to incorporate monitoring equipment in the bioretention cell during construction. Meteorological uncertainty also becomes a problem when relying on natural
precipitation events to conduct evaluations, as they are impossible to control and difficult to replicate (Weiss et al., 2007). Simulated runoff has been used as a source of water to combat the difficulties in relying on natural storm events. A simulated runoff test is advantageous compared to ring infiltration tests for measuring rain garden infiltration performance in that it provides a direct measure of the rain garden drain time and provides a systematic infiltration evaluation (i.e. infiltration is integrated over the entire area) rather than highly variable soil infiltration tests at discrete locations in the basin.

Asleson et al. (2009) used a constant flow rate from a fire hydrant to conduct synthetic runoff tests on twelve rain gardens in Minnesota. Davis et al. (2001) used synthetic runoff to study rain gardens in Maryland. This study involved the application of simulated runoff for six hour durations, which may or may not be representative of field conditions for an actual rain garden. Studies evaluating the effectiveness of vegetated buffer strips have also used simulated runoff. Franti et al. (2007a) has conducted an extensive literature review showing a lack of variable flow testing on these agricultural BMPs.

Materials and Methods

This project involved using a runoff simulator to evaluate hydrologic characteristics of residential rain gardens in Lincoln, Nebraska. The objective of this study was to use this simulator to determine the hydrologic function and storage properties of 12 existing rain gardens in order to evaluate design features, including:

- In-situ storage depth and volume
- Outflow structure and function
- Infiltration rate
- Soil profile characteristics

Site Description

The Holmes Lake watershed is a 1,400 hectare watershed in southeastern Lincoln, Nebraska draining into Holmes Lake, a 45.3 hectare (111.9 acre) flood control reservoir listed in section 303(d) as impaired for nutrients, dissolved oxygen, and sediment (US EPA, 2011). The dominant soil type in the watershed (35% by area) is Aksarben silty clay loam (Soil Survey Staff, NRCS, 2011), which is classified as an NRCS Hydrologic Soil Group C soil. In June 2007 the City of Lincoln initiated the Holmes Lake Watershed Improvement Program with incentives for citizens who were interested in obtaining rain gardens, rain barrels, and no-phosphorus fertilizer. The City of Lincoln, based on continued grant assistance and participant demand, expanded the original rain garden cost-share program city-wide after the first year.

All rain gardens in the program were installed by Campbell's Nursery in Lincoln, Nebraska. Nine sites for this study were chosen from this pool of original rain gardens built in 2007, located within the Holmes Lake watershed boundary (fig 1). Two sites were chosen from the 2008 installations, and one site was chosen from the 2009 installations. This 2009 site is the only rain garden in this study not located within the watershed boundary, but is located in the same region of Lincoln. This site is similar to the remaining sites in that it is located on land designated as hydrologic soil type C (NRCS Web Soil Survey, 2011).

This project involved evaluating the hydrology of rain gardens in the Holmes Lake watershed using a modified version of the runoff simulator developed by Franti et al. (2007a; 2007b) and Alms et al. (2011).
Rain garden sizes varied, ranging from 4.8 to 12.7 m². Sites also showed surface area-to-drainage area ratios (hereafter referred to as loading ratios) of 7.1 to 24.8%, with additional variation in percentage of impervious catchment present (Table 1). Catchment areas in this study represent contributing areas minus the area of the BMP. The design storm calculations, however, do include the garden area.

Table 1. Background information on rain garden sites in Lincoln, Nebraska

<table>
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<tr>
<th>Rain Garden Site</th>
<th>Surface Area (m²)</th>
<th>Install Date</th>
<th>Roof Contributing Area (m²)</th>
<th>Total Catchment Area (m²)</th>
<th>A_{garden}/A_{imp_catch} (%)</th>
<th>A_{garden}/A_{total_catch} (%)</th>
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<td>49.7</td>
<td>49.7</td>
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<td>14.1</td>
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<td>10.7</td>
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<td>72.8</td>
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<tr>
<td>SD</td>
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<td>--</td>
<td>20.3</td>
<td>29.9</td>
<td>8</td>
<td>7</td>
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**Simulator**

Simulated stormwater runoff was applied to each rain garden using a modified version of the runoff simulator developed successively by Franti et al. (2007a; 2007b) and Alms et al. (2011). The simulator had shown the ability in past studies to accurately replicate input hydrographs in controlled environments. For this study, the simulator was modified to be mobile for use in residential settings and to use municipal water derived from fire hydrants (fig. 2). The control system consisted of a McCrometer full bore magnetic flow meter (Hemet, Calif.), an A-T Controls V-port control valve (Cincinnati, Ohio), a National Instruments Compact Data Acquisition
System (Austin, Texas), and a control program written by Alms et al. (2011) in LabView™ 8.2 (Austin, Texas). Figure 2 shows the schematic of the system.

Prior to the rain garden testing in the summer of 2011, both laboratory and field testing were performed. This involved calibrating the v-port valve position to a defined signal with water in the pipe, resulting in a calibration output file of amps vs. “percent ball valve open” that was used in all rain garden simulations. Additional calibration was done to ensure that both the magnetic meter and pressure sensor functioned for a range of input signal values. As the magnetic meter and valve each display flow readings, validation using a plastic tank and pressure transducer with a range of water flows was performed to determine which device displayed the most accurate flow rate.

At each rain garden site, two different runoff events were applied. The first event was the water quality volume (hereafter referred to as WQV) precipitation event for Lincoln, Nebraska, or the 90th percentile historical rainfall event determined from National Climatic Data Center records for the Lincoln Municipal Airport (NCDC, Asheville, North Carolina). Using 24-hour precipitation data (SUDAS, 2009) and excluding events less than 0.25 cm (US EPA, 2009), Lincoln’s WQ rainfall event was determined to be 3.0 cm (1.2 in.). The second event was designed to have a volume sufficient to over-top the rain garden berms so that the integrity of the overflow structure could be observed. The peak hydrograph flow rate for the overflow event was typically between 1.5 and 2 times the peak of the design storm. The runoff was administered to the garden at the most discernible inlet based on observation and/or survey data. Inlet protection using a slotted PVC well screen and a burlap bag was used to minimize erosion.

Hydrographs for each site were calculated using the Natural Resource Conservation Service (NRCS) curve number loss method with an initial abstraction-to-storage ratio of 0.05 (Woodward et al., 2004). Roof and lawn surfaces (hydrologic soil groups C and D) were assumed to have curve numbers of 98 and 77, respectively (USDA-NRCS, 1986). The kinematic wave transform method was employed in HEC-HMS 3.4 software (Davis, Calif) given the predominance of
planar roof flow in the total influent volume (Heasom, 2006). Due to uncertainty of measured outflow rate below 0.75 L s\(^{-1}\), all hydrographs were adjusted to meet or exceed this flow while maintaining the same runoff volume, resulting in slightly time-compressed hydrographs.

Ponding in each rain garden was measured using a Solinst Levelogger (M5 LT) pressure transducer (Solinst Canada Inc., Georgetown, ON, Canada). The transducer was situated in a 5.1 cm-diameter PVC stilling well installed at the lowest point in the rain garden based on a transect survey. Stage-storage relationships for each garden were also developed. Average ponding depth was computed by dividing the calculated storage volumes by the measured surface areas at the stage of maximum ponding. The percent of applied volume before overflow (surface storage volume plus any that infiltrated prior to overflow) relative to the design storm was calculated. For this analysis, rain gardens which were found to have surface storage volumes within 10% of the water quality volume were considered “acceptable” (Wardynski and Hunt, 2012).

The application of each design storm hydrograph proceeded until overflow at any location was observed. The simulation was then stopped using the control program in LabVIEW, and the highest water line was marked with flags around the ponded perimeter. From this point, drawdown infiltration was observed until transducer data indicated the rain garden had fully drained. Follow-up surveys were conducted to integrate the flagged perimeter of ponding into the original survey data. The second simulated runoff event for each rain garden was conducted to observe potential weak points in the berm and note any erosion issues.

**Data Analysis**

SAS 9.2 statistical software (SAS Institute, Inc., Cary, N.C.) was used for all analyses with a 95% confidence level \( (\alpha = 0.05) \). Specifically, the effects underlying soil type, cell size, ponding depth, and loading ratio were analyzed using experimentally-determined storage volume, infiltration rate, and drawdown time data. These tests were carried out using a linear model procedure \( (\alpha = 0.05) \) with treatment interactions examined. Pearson coefficients of correlation were calculated for each tested effect with an assumption of normality. All parameters with correlation (R) magnitudes greater than 0.5 were considered highly correlated.

To eliminate transducer-related field noise in the surface area and storage volume curves (both with respect to time), both data sets were plotted in SigmaPlot with nonlinear regression curves (power and exponential) generally having a coefficient of determination of 0.99. A stepwise infiltration rate was calculated for all rain garden tests using these data curves. Using the Double-End Area Method (ADOT, 2005), the average surface area between each time step was computed. This value, and the change in volume over the same time step, yielded an area-averaged infiltration rate as shown below in equation 1.

\[
I_{1-2} = \frac{[A_{1} + A_{2}]}{2} \left[ \frac{V_{1} - V_{2}}{A_{0}} \right]
\]

Because infiltration rate typically decreases as soil water content increases (Ward, 2004), one value could not accurately represent drainage rate for the entire event. As a result, a minimum or pseudo-steady state infiltration rate value was estimated based on the curves, which represents a conservative value when comparing to rain garden design manual values.
Results

Storage Characteristics

None of the rain gardens evaluated had adequate surface storage capacity to hold the design storm. Two rain gardens (sites 1 and 11) retained 93 and 99% of the design storm, respectively. This metric of retention of the design storm included infiltration volume before the simulation ended (i.e. overtopping of the berm occurred) and surface storage volume. By this standard, sites 1 and 11 were deemed to meet the design criteria. Figure 3 shows the lack of adequacy for all rain gardens to hit the target 1:1 line, which represented full design storm retention in the surface basin. Figure 3 also shows that sites 1 and 11 managed to infiltrate or store the entire applied design storm. Table 2 shows various retention characteristics of each rain garden. The other ten gardens were well below the capacity needed to contain the WQV. On average, a wide range of retention capacities before overflow was noted, ranging from 7 to 99% (±SD = 32%) with a mean of 40%. Percentages of the design storm retained and equivalent precipitation event were not calculated for site 2 and 4. Site 2 had no storage capacity, essentially routing water directly through it with little to no retention. The design storm volume data for site 4 is unavailable due to human error.

![Figure 3. (Left) Rain garden surface storage capacity plotted against the design storm. (Right) Total storage (including infiltration during event) plotted against the design storm volume. Lines represent 1:1 and 2:1 slopes.](image)

<table>
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<td>41%</td>
<td>23%</td>
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Ponding Depth

The average maximum water depth before overflow for all sites (excluding site 2) was 8.9 cm (3.5 in.) (Figure 4). Various recommendations for ponding depth range from 8 to 30 cm (3 to 12 in.), with 15-23 cm being typical (Franti and Rodie, 2007; Hunt, 2001). These depth guidelines assume a flat mulch rain garden surface. No strong correlations were found between ponding depth and infiltration rate and drawdown time. A slight correlation (R = 0.422, p = 0.011) was found between depth and the percent surface storage filled by the design storm. Maximum depths ranged from 7.6 to 12.4 cm (3.1 to 4.9 in.) for the 11 sites. The high variability is evident by the spread of data in the box and whisker plot below. Ideal rain garden / bioretention grading should show much less variability, with a tight spread around the mean. The mean basin-averaged depth within the wetted perimeter of the design storms was 4.0 cm for all sites, ranging from 1.8 to 7.7 cm. The basin-averaged garden depths were significantly lower than the maximum depths (p < 0.001). The results of the analysis of average depth indicate the gardens are shallower than is recommended by current rain garden guidelines.

![Figure 4. Box and whisker plot of rain garden depths measured at various spatial points from the mulch surface to maximum water depth before overflow.](image)

Drainage Time

The mean drainage times (±SD) for the WQV event and the overflow event were 1.61 h (±1.81) and 5.54 h (±8.90), respectively, with a maximum time recorded of 30 h. The measured drainage times of the twelve rain gardens are plotted in Figure 5. No overflow event was simulated for site 2; because of the lack of storage volume for the WQV, the decision was made to forego the second test and collect all necessary data in one event. All drain times were less than the 48 hour recommended maximum drainage time allowable in bioretention (US EPA 1999; Franti and Rodie, 2007; Wisconsin Department of Natural Resources, 2003).
Soil Properties

83% of the rain gardens assessed had USDA-classified loam surface soils (table 5). As expected, the underlying soil profile (7-39 cm) showed higher clay content than the surface soils (p < 0.001), with a mean of 36% (±SD = 3.3%). As a result, the predominant classification of these underlying soils was silty clay loam and clay loam (58% and 25% of gardens, respectively). Compared to bioretention, all rain gardens in this study exceed the recommended clay and silt content. Organic matter was significantly higher in the surface layer (p = 0.003) than in the subsurface, possibly indicating the surface has the ingredients for a more active biological system.

Bulk density (dry basis) of the amended surface soil ranged from 0.56 to 1.11 g cm⁻³ with a mean (± SD) of 0.88 g cm⁻³ (0.16 g cm⁻³). All of the bulk density values were lower than the “critical” bulk density value of 1.4 g cm⁻³ defined by Jones (1983) to be the density at which plant root penetration is likely to be severely restricted.

Infiltration Rate

The rain garden design storm simulations yielded minimum infiltration rates ranging from 0.18 to 70.4 cm h⁻¹. Three rain gardens showed minimum infiltration rates below 1 cm h⁻¹, which are below the three selected national bioretention design guidance drainage recommendations (Table 3). A Shapiro-Wilkes test for normality indicated that the log-transformed minimum infiltration rate values follow a normal distribution (W = 0.926, p = 0.398). Therefore, the geometric mean was used to compute a mean for both the design storm and overflow event drainage infiltration rates for this study. The geometric mean of all design storm minimum infiltration rates was 4.13 cm h⁻¹ (± 26.7 cm h⁻¹), which exceeds the conservative criteria of 2.54 cm h⁻¹ from the Prince George’s County, Maryland bioretention guideline. Eight of eleven rain gardens tested met or exceeded the Nebraska rain garden design guide published by the University of Nebraska-Lincoln Cooperative Extension (Franti and Rodie, 2007).
Table 3. Infiltration rate comparison between rain gardens and established design guides during two simulated storms for both faster events (gray) and slower events (white). Infiltration rates greater than 20 cm h\(^{-1}\) were considered “fast”.

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<th>Site ID</th>
<th>EVENT 1 (DESIGN STORM)</th>
<th>EVENT 2 (OVERFLOW STORM)</th>
</tr>
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<td>Minimum Infiltration Rate (cm h(^{-1}))</td>
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<td>1.37</td>
<td>Y</td>
</tr>
<tr>
<td>8</td>
<td>3.65</td>
<td>Y</td>
</tr>
<tr>
<td>10</td>
<td>0.40</td>
<td>N</td>
</tr>
<tr>
<td>12</td>
<td>16.20</td>
<td>Y</td>
</tr>
</tbody>
</table>

G.M.[f] Fast: 51.1 ± 23.8
G.M. Slow: 1.61 ± 5.3
G.M. All: 4.13 ± 26.7

[a] Infiltration rate recommendations are listed below each design guide.
[b] University of Nebraska-Lincoln Extension Publication G1758 “Rain garden design for homeowners.”
[c] Wisconsin Department of Natural Resources rain garden guide
[d] Prince George’s County, Maryland Bioretention Guide
[e] “Y” = yes, does meet respective guide’s criteria; “N” = no, does not meet criteria
[f] Geometric mean

The rain gardens evaluated in June had high initial soil moisture contents, likely due to above average precipitation for the month (150% of normal). July experienced below-average precipitation (75% of normal), but the soil moisture content of the surface soils of the rain gardens evaluated in this month were statistically identical to the June data set (p = 0.89). The two sites where the greatest infiltration rates were measured (sites 9 and 11) were also characterized by the lowest and fourth lowest initial soil moisture values (0.34 and 0.40 cm\(^3\) cm\(^{-3}\)), respectively. The presence of clay shrinkage-related cracks combined with lower antecedent soil moisture likely contributes to greater infiltration rates. Note: infiltration rate was only measured for 11 sites because site 2 did not have appreciable storage, resulting in a lack of drawdown data.

The minimum infiltration rates for the design storm of each site showed strong negative correlation (R = -0.722; p = 0.006) with initial soil moisture. This fits the trend described above, that as initial soil moisture increases, minimum infiltration rates decrease. The overflow storm infiltration rate was also correlated with antecedent moisture content (R = -0.618; p = 0.024), but because only the design storm had a measured antecedent moisture, the correlation does not have much of a physical basis to relate to.

Overflow Structure

Rain garden overflow structures are meant to be placed at the proper elevation to insure weir-like overflow occurs when the ponded zone is full of water (Figure 5). Most of the gardens evaluated had poorly designed or constructed overflow structures that may have contributed to an inability to store the water quality volume. Overflow structure design flaws included:
• Poor grading resulting in the outflow structure not being the lowest elevation of the berm. (Figure 5a)
• Lack of overflow structure (Figure 5b)
• Lack of adequate rock or erosion control at the overflow structure weir (Figure 5c)
• Inadequate width of outflow weir to pass larger flows before widespread overtopping of the berm occurs.

Figure 5. Photographs of failed overflow structures. (a) Outflow is at a low spot of the berm. (b) Lack of overflow structure. (c) Erosion of mulch on a berm.

Of the ten rain gardens that did have defined outflow structures, four were deemed failing based on: (1) the designated rock weir structure was not the location of water first escaping and/or (2) the outflow structure remained dry during the entirety of the second simulated event. Water flowing out of the rain garden at site 11 had four distinct outflow locations, none of which were the designed weir structure. Among these four sites, two (9 and 10) had preferential flow paths directly onto the impervious driveway because insufficient berm and outflow grading.

Two rain gardens (sites 4 and 8) did not have discernible overflow structures. Both sites, however, were observed to have one distinct preferential berm location over which water flow was consistently maintained during the overflow storm. Both of these berms were populated with turf grass. From an erosion control standpoint, this may have been beneficial, as the grass prevented mulch and soil from overtopping the berm; however, excessive grass on the berm can encroach in the garden itself, disrupting the native perennials. It should be noted that site 8 just mentioned did not have an overflow structure likely because there was a drop structure outlet with a grate buried opposite the inlet. This was not discovered until the day of the simulation. This outlet was subsequently plugged by plastic and sandbags to simulate no under drain conditions, allowing the researchers to observe grass berm overflow.

To some degree, every site had a large amount of mulch that floated during the simulation. This mulch slowly migrated to the overflow structures (if present), where it often caused a “mulch dam” to form. This reduced the effectiveness of the rock structure, which is supposed to pass water smoothly much like a weir. In some cases, the runoff carried mulch over the top of the outlet structure. This occurred most notably at sites 5 and 6. The site 5 rain garden mulch washout (pictured in Figure 5a) resulted in the reconstruction of the berm in that area and reinforcement of the rock overflow structure.
Conclusions

With respect to the current design paradigm of volume-based control for rain gardens, which promotes designing the basin to store the entire water quality volume on the surface, the rain gardens evaluated in this study were inadequate. No rain garden met the “acceptable” standard for volume retention on the surface (±10% of the design storm volume), with the “best” design storm capacity being 23%. When accounting for water that infiltrated before overtopping, two rain gardens were “acceptable” (90 and 99% volume capture).

Inability for the rain gardens to manage the water quality volume is likely not due to low infiltration rates. Rather, the lack of properly-constructed storage bowls is much more likely to be the culprit. The large coefficients of variation from surface survey data and uneven berm elevations were found in many sites. Of the ten gardens demonstrating premature overflow, eight had discrete, armored low points functioning as overflow structures. Of these eight, only three routed flow over these structures. Of the sites demonstrating a fully-functioning overflow structure during excessive flows, only 50% of the garden surface area was inundated, indicating improper grading practices.

Pseudo steady-state infiltration rates of the rain gardens generally met the Nebraska design guide drawdown rate. Similarly, drainage times for all sites were less than the 48-hour maximum ponding time generally cited by rain garden and bioretention design manuals. The average drawdown time was 1.6 h. Drainage times for the second simulated storm met the guidelines as well, with 5.5 h average drain times.

The study showed that infiltration rate was strongly correlated to initial soil moisture of the surface. However, the two sites with relatively high initial soil content (0.5 cm$^3$ cm$^{-3}$) had design storm minimum infiltration rates of 4.1 and 1.4 cm h$^{-1}$, which exceeded recommended standards. Understandably, infiltration rate was strongly correlated with drain time.

A consistent theme at the twelve rain gardens was inadequate berm grading. While an overflow may be installed with enough rock and be at the right location, a breach or low point in the berm at another location resulted in a less effective storm water retention structure.

Recommendations

The following is a discussion of the ranges of design changes one could make to better store and infiltrate the water quality volume event

While re-grading the garden basin to achieve a uniform depth may not be feasible for established rain gardens, ensuring no more mulch than necessary is applied can increase storage. Additionally, the homeowner could create a uniform depth above the mulch layer during mulch replacement.

One important factor that affects the rain gardens’ ability to capture the full water quality volume is the catchment area relative to the size of the basin. The literature extensively discusses garden surface area-to-impervious catchment ratios. Rain garden design guides vary in their recommendations on this value, suggesting rain garden areas be anywhere from 3 to 43% of the catchment area (Hunt and Lord, 2005; Wisconsin DNR, 2003; Schmidt, 2007; Stander, 2009). A wide range of garden-to-catchment ratios was observed within this study (6-30%, Table 1). A critical investigation should be undertaken to determine if this metric is a valid design metric, or if it should be abandoned. Li et al. (2009) suggests that media depth alone
proved to be far more important than cell surface area to drainage area ratio in Maryland and North Carolina.

This study shows that infiltration rate and drawdown time data for a group of established rain gardens in/near the Holmes Lake watershed in Lincoln, Nebraska do not seem to be the limiting factor to rain garden performance. The true culprit for poorly performing rain gardens is poor grading and inadequate surface storage before overflow. Deeper, less variable basin depth gardens can ensure not only an even distribution of water, but efficient treatment of catchment area runoff by reducing the surface area footprint.

References


Prince George’s County, Maryland. 2007. *Bioretention manual*. Prince George’s County, Maryland Department of Environmental Resources.

Schmidt, R., D. Shaw, and D. Dods. 2007. *Blue thumb guide to raingardens: Design and installation for homeowners in the upper Midwest*. Waterdrop Innovations, LLC.


