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HYDROLOGIC EVALUATION OF RESIDENTIAL RAIN GARDENS USING A STORMWATER RUNOFF SIMULATOR

A. R. Anderson, T. G. Franti, D. P. Shelton

ABSTRACT. Engineered bioretention cells with underdrains have shown water quality and hydrologic benefits for abating urban stormwater problems. Less is known about the hydrologic performance of residential rain gardens that rely on in situ soil infiltration as the primary mechanism of volume control. Eleven residential rain gardens in Lincoln, Nebraska, were evaluated using a variable-rate stormwater runoff simulator. A volume-based water quality volume (WQV) design storm of 3.0 cm was applied to each rain garden as an SCS Type II runoff hydrograph until the system began overflowing to test the rain gardens for surface and subsurface storage capacity, drawdown rate, ponding depth, and overflow characteristics. Every rain garden tested drained in 30 h or less, with six gardens draining in less than 1 h. Rain garden surface storage capacity was poor, retaining on average only 16% of the WQV. On average, the rain gardens studied could store and infiltrate only 40% of the WQV, with only two gardens able to store and infiltrate greater than 90% of the WQV. On average, 59% of the runoff was captured as subsurface storage. Results of this study indicate that these 2- to 4-year-old rain gardens are limited not by drain times and rates, which often met or exceeded common design recommendations, but rather by inadequate surface storage characteristics. Extrapolating measured surface storage volumes to hypothetical systems with evenly graded depths of 15.2 cm, a minimum local depth recommendation, resulted in only one garden with enough storage to contain the WQV. On average, the extrapolated storage held only 65% of the WQV. It was shown that subsurface storage can make up for a lack of surface storage; the systems studied herein had an average of 2.7 times more subsurface storage than surface storage as a percentage of inflow volume before overflow began.

Keywords. Best management practice, Low-impact development, Rain garden, Runoff simulator, Stormwater.

Urban stormwater runoff is a major factor contributing to the impairment of water bodies in the U.S. Conventional urban development involves constructing gutters, storm sewers, and paved channels, causing increased peak flows, increased runoff volumes, and decreasing the lag time of runoff hydrographs (Leopold, 1968; Line and White, 2007; Schueler et al., 2009). This hydrologic change can disrupt the sedimentation and erosion equilibrium of receiving channels, resulting in channel incision and widening and bank failure, causing property damage and loss of habitat for aquatic species (USEPA, 2004). In 1999, Prince George's County, Maryland, integrated best management practices (BMPs) with policy making and land planning, thus pioneering the comprehensive watershed management technique known as low-impact development (LID).

The goal of LID is to return a site or watershed to a pre-development hydrologic condition through stormwater volume reduction and pollution prevention measures that com-

pensate for land development (PGCo, 1999). This is achieved largely by the ability of LID practices to lower peak flow rates, increase lag times to the peak, reduce runoff coefficients, reduce runoff thresholds, and reduce runoff volumes for moderate to small storm events (Hood et al., 2007; Gilroy and McCuen, 2009; Page et al., 2015). In the last two decades, LID has been shown to be an effective way to decentralize stormwater management by implementing multiple structural and nonstructural controls to improve the hydrologic response of a watershed (Dietz, 2007). One particularly effective class of BMP used to accomplish LID is bioretention.

In this article, bioretention refers to vegetated depressions used to store and soak stormwater runoff into a subsurface soil. Bioretention in this definition includes systems with engineered subsurface media and/or underdrainage systems, as well as systems that rely solely on infiltration and percolation into *in situ* soils for runoff reduction (bio-infiltration).

Research on the water quality and hydrologic characteristics of larger, more complex bioretention systems has been progressing since the introduction of the concept in the Chesapeake Bay region (Coffman et al., 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, 2009; Dietz, 2005; Hunt et al., 2006; Davis, 2008). A number of studies on bioretention cells with an underdrain have used an impermeable liner between the native soil and engineered soil to capture inflow and reduce exfiltration to achieve a mass balance for

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water quality analysis purposes (Houdeshel et al., 2015; Li et al., 2009; Kim and Seagren, 2003).

While performance knowledge is growing for large-scale bioretention systems that use an underdrain outflow structure, less research exists on smaller, residential-scale bio-infiltration cells that rely solely on percolation into native soil as the mechanism for primary treatment. This article refers to such systems as “rain gardens” per common usage in municipalities across the U.S. (Bannerman and Considine, 2003; Alliance, 2017; MARC, 2017; Rutgers, 2017). Siting bioretention systems on private residential property can be a barrier to their adoption in stormwater management plans, as it requires oversight of installation and maintenance (Morzaria-Luna et al., 2004).

Rain gardens on the homeowner scale are typically designed to capture about 13 to 40 mm of rainfall. Some rain garden guidance documents simplify the surface area sizing of a rain garden to be a function of the size of the watershed. For example, North Carolina Cooperative Extension (NCCE, 2014) suggested sizing a rain garden basin at 10% of the contributing impervious area. Rain gardens are often dug to varying depths depending on local guidance, ranging from 100 to 250 mm (Bannerman and Considine, 2003; Franti and Rodie, 2013; NCCE, 2014). It is generally desirable to construct the final rain garden grade to be relatively flat to maximize the amount of water stored and prevent preferential flow paths. This surface is typically mulched and vegetated. The perimeter of a rain garden is often bermed to provide the desired storage depth. Finally, a small broad-crested weir structure is often carved into the berm to provide a controlled overflow point to bypass runoff that exceeds the rain garden’s capacity. Figure 1 shows a basic grading schematic of a rain garden with common water control features and terminology. Most publicly available guidance documents include designs predicated on infiltrating a theoretically full rain garden within a certain duration to (1) reduce the likelihood of mosquito larvae development in standing water, and (2) restore the storage volume in anticipation of the next rainfall event.

Testing of the performance of homeowner-maintained rain gardens is scarce in the literature; however, such work may provide a more realistic evaluation of the hydrologic and functional conditions of established residential rain gardens (USEPA, 2002). Season-long monitoring of a single BMP is sometimes impractical because of the time and resources required, as well as the effort sometimes needed to incorporate monitoring equipment into the bioretention cell during construction. Meteorological uncertainty also be-

comes a problem when relying on natural precipitation to conduct evaluations, as it is impossible to control and difficult to replicate rainfall and runoff characteristics across events (Weiss et al., 2007). Simulated runoff has been used to address the difficulty of relying on natural storms. Asleson et al. (2009) used simulated runoff to fill rain gardens to assess drain times and generally found good agreement between drain times and measured infiltration rates using a modified Philip-Dunne infiltrometer. Davis et al. (2001) used simulated runoff to study rain gardens in Maryland, which involved application of simulated runoff for 6 h durations. Lucke et al. (2015) subjected three field-scale bioretention basins to four simulated rainfall runoff tests that had variable flow rates and found volume reductions ranging from 32.7% to 84.3% for the three cells.

METHODS AND MATERIALS

This research used a runoff simulator to evaluate the hydrologic characteristics of residential rain gardens in the Holmes Lake watershed in Lincoln, Nebraska. The objective of this study was to evaluate the following characteristics of eleven existing rain gardens:

- Water storage capacity, both surface storage in the rain garden basin and subsurface storage before overflow occurs.
- Ponding depth, both the maximum water depth above the mulch before overflow occurs and the variability in this depth across the surface of the rain garden.
- Drawdown rate, defined as the vertical drop in water level over time.
- Overflow structure and function.
- Soil characteristics.

SITE DESCRIPTION

The Holmes Lake watershed is a 1400 ha watershed in southeastern Lincoln, Nebraska. Holmes Lake is a 45.3 ha flood control reservoir listed in the Clean Water Act Section 303(d) as impaired for nutrients, dissolved oxygen, and sediment (USEPA, 2011). The dominant soil type in the watershed (35% by area) is Aksarben silty clay loam (USDA, 2011), which is classified as an NRCS Hydrologic Soil Group C soil. As part of the 2007 Holmes Lake Water Quality Improvement Program, 18 free and cost-share rain gardens were funded and installed by the city of Lincoln. In 2008 and 2009, the rain garden incentive program was expanded citywide, resulting in 76 homeowner installations

Figure 1. Schematic of rain garden without an underdrain showing typical features.

around the city (Meder and Kouma, 2010). The rain gardens were installed as a pilot cost-share program and were not designed explicitly to hold the water quality volume (WQV) but rather to be functioning rain gardens and acceptable landscape features for the homeowners. Size, location, and depth were selected by a local nursery's landscape designer in collaboration with each homeowner. The final size varied based on available yard space, homeowner preference, and construction quality control.

For this research, seven sites were chosen from the 2007 installations, three sites were chosen from the 2008 installations, and one site was chosen from the 2009 installations. All chosen sites had been installed by the same local nursery. The 2009 site is not within the watershed boundary (2.5 km southeast of the watershed) but has the same HSG classification as the other sites (fig. 2). Rain garden sizes varied, ranging from 4.8 to 12.7 m². Sites were chosen based on homeowner participation, proximity to fire hydrants, and observed integrity of the rain garden using professional judgement. Site 2, while evaluated initially, had virtually no discernable storage characteristics and thus was not included in the further analysis. The sites exhibited surface area to drainage area ratios of 6% to 25%, comprising rooftop and lawn catchments (table 1). For comparison, North Carolina's rain garden manual recommends a 10% surface area to drainage area ratio for rain gardens, while larger, more engineered bioretention systems often have values in the 5% to 20% range (PGCo, 1999; Pennsylvania, 2006; NCCE, 2014; Philadelphia, 2017). In bioretention generally, as the surface area to

drainage area ratio is increased, the outflow volume is reduced (Hatt et al., 2009; Jones and Hunt, 2009).

SIMULATOR

Simulated stormwater runoff was applied using a modified version of the storm runoff simulator reported in previous studies (Franti et al., 2007a, 2007b; Alms et al., 2011). The simulator had shown the ability to accurately replicate input hydrographs in controlled environments (fig. 3). For this study, the simulator was modified to be mobile for use in residential settings and to operate using municipal water drawn from fire hydrants (fig. 4). The control system consisted of a full-bore magnetic flowmeter (McCrometer, Hemet, Cal.), a V-port control valve (A-T Controls, Cincinnati, Ohio), a compact data acquisition system (National Instruments, Austin, Tex.), and a control program written by Alms et al. (2011) in LabVIEW (ver. 8.2, National Instruments, Austin, Tex.). Prior to the rain garden testing in the summer of 2011, both laboratory and field testing of the simulator were performed. This testing involved calibrating the V-port valve and magnetic flowmeter using plastic tanks and pressure transducers with a range of water flows.

At each rain garden site, two different runoff events were applied. The magnitude of the first simulated runoff event was equivalent to the WQV for Lincoln, i.e., the 90th percentile historical rainfall event determined from National Centers for Environmental Information (Asheville, N.C.) records for Lincoln Municipal Airport. The 90th percentile event is a widely used WQV for stormwater BMPs as a com-

Figure 2. Map of the Holmes Lake watershed and the rain garden sites in Lincoln, Nebraska.

Table 1. Rain garden site information.

Site	Surface Area (A_{garden} , m ²)	Year of Installation	Roof Catchment Area (A_{roof} , m ²)	Total Catchment Area (A_{total} , m ²)	$A_{\text{garden}} / A_{\text{roof}}$ (%)	$A_{\text{garden}} / A_{\text{total}}$ (%)
1	10.2	2007	49.7	49.7	20.6	20.6
3	10.7	2007	36.5	109.2	29.4	9.8
4	9.2	2007	51.2	118.1	18.0	7.8
5	4.8	2007	77.7	77.7	6.2	6.2
6	7.9	2007	79.4	112.0	10.0	7.1
7	5.6	2007	22.9	22.9	24.3	24.3
8	9.0	2007	29.6	38.9	30.4	23.1
9	12.7	2008	51.1	51.1	24.8	24.8
10	11.7	2008	70.3	70.3	16.6	16.6
11	11.3	2008	52.6	72.3	21.6	15.7
12	9.8	2009	86.9	86.9	11.3	11.3
Mean	9.4	-	55.3	73.6	19	15
SD	2.3	-	21.1	31.3	8	7

Figure 3. Runoff simulator with tank, trailer, and pump. The valve and flowmeter are shown in the inset.

promise between capturing pollutant loads from smaller events and the cost-effectiveness of the practice (Schueler et al., 2007; Maryland, 2009; Franti and Rodie, 2013; Guo et al., 2014). Using 24 h precipitation data and excluding events less than 0.25 cm (SUDAS, 2009; USEPA, 2009), Lincoln's WQV was determined to be 3.0 cm. The second event (event 2) was designed to provide a water volume sufficient to overtop the rain garden berms so that the integrity of the overflow structure could be observed. The design runoff volume was chosen to be 3 times the WQV, and the peak overflow for this hydrograph was typically between 1.5 and 2 times the peak of the WQV. Water was delivered to the

garden at the most discernible inlet point based on observation and/or survey data. Inlet protection consisting of a slotted PVC well screen and a burlap bag was used to minimize erosion.

Inflow hydrographs for each site were calculated using the NRCS curve number (CN) method with an initial abstraction-to-storage ratio of 0.05 (Woodward et al., 2003). Roof and lawn surfaces were assumed to have CNs of 98 and 77, respectively (USDA, 1986). The kinematic wave transform method was employed in HEC-HMS 3.4 software (U.S. Army Corp of Engineers, Hydrologic Engineering Center, Davis, Cal.) to develop a temporally dynamic hydro-

Figure 4. Schematic of runoff simulator used for rain garden evaluations.

graph to simulate fluctuations in inflow rate. Table 2 details the peak flows programmed into the simulator software for each site. Because of the difficulty in measuring flows below 0.75 L s^{-1} with the magnetic flowmeter, all hydrographs were programmed to a minimum flow rate of 0.75 L s^{-1} while maintaining the same runoff volume, resulting in slightly time-compressed hydrographs of a design duration of 30 min, a duration that has since been replicated in a bioretention runoff simulation study by Lucke et al. (2015).

The ponding depth in each rain garden was measured using a pressure transducer (Levellogger M5 LT, Solinst Canada, Inc., Georgetown, Ontario, Canada). The transducer was situated in a 5.1 cm diameter PVC stilling well installed at the lowest point in each rain garden. The transducer remained saturated throughout each test, with the datum of measurement of the transducer approximately 13 cm below the mulch/surface interface. Total station surveys were performed to produce stage-storage relationships for each site,

Table 2. Individual site storage characteristics.

Site	Calculated WQV (L)	Peak Flow of WQV Event (L s^{-1})	Water Applied before Overflow (L)	Surface Storage Capacity (L)	Volume Infiltrated before Overflow (L)	Applied Volume Infiltrated before Overflow (%)	Retained Volume as Percent of WQV (%)	Retained Volume on Surface as Percent of WQV (%)	Equivalent Precipitation Depth Stored before Overflow (cm)
1	1,569	1.65	1,464	306	1,158	79	93	20	2.84
3	1,484	2.55	570	127	443	78	38	9	1.47
4	1,852	3.58	-	640	-	-	-	35	-
5	2,531	3.14	338	151	187	55	13	6	0.60
6	2,388	2.90	160	75	85	53	7	3	0.41
7	750	1.46	158	91	67	43	21	12	0.84
8	1,062	1.28	382	228	154	50	36	21	1.29
9	1,679	2.35	591	182	409	69	35	11	1.25
10	2,078	2.47	323	179	145	45	16	9	0.69
11	1,762	1.94	1,738	393	1,344	77	99	22	2.99
12	2,499	2.96	1,034	585	449	44	41	23	1.45
Min.	750	1.28	158	75	67	43	7	3	0.41
Mean	1,787	2.39	676	269	444	59	40	16	1.38
Max.	2,531	3.58	1,738	640	1,344	79	99	35	2.99
SD	571	0.74	553	194	451	16	32	9	0.89

to determine the low point in the garden, and to discern the inlet/outlets (if not evident from observations). For each garden, the survey-derived maximum storage volume was then compared to the WQV.

Maximum ponding depth was compared to average ponding depth to assess the uniformity of grading of the rain garden basin, which affects the volume of surface storage. Maximum ponding depth was measured at the lowest basin elevation. Average basin soil surface elevations were determined based on the surveyed surfaces of the rain gardens. The values used for average depth were restricted by the planar area that was wetted during the simulation (i.e., the dry portions of a garden were not considered in this calculation of average depth).

The first WQV hydrograph inflow proceeded until overflow was observed at any location along the berm. This occurred at different points on the hydrograph for each rain garden as a percentage of the whole hydrograph due to differences in storage capability before overflow. The simulation was then stopped, and the highest water line was marked with flags around the ponded perimeter. The total volume of water that was stored on the surface of the rain garden and as subsurface soil storage was measured as the volume through the magnetic flowmeter during the simulation. Next, drawdown was observed until the transducer data indicated that the rain garden had fully drained. For site 4, where the cumulative inflow volume data were lost, the ability to estimate surface and subsurface storage as a whole was not possible. The surface-only storage for this site was estimated using the stage-storage relationship developed through the field survey and the pressure transducer depth at the observed time of overflow. Follow-up surveys were conducted to integrate the flagged perimeter of ponding into the original survey data. The second simulated runoff event, the berm overflow event, was conducted to observe potential berm erosion issues, as well as determine average drawdown rates in a more saturated soil (i.e., conservative case).

SOIL DATA

Prior to runoff simulations, six or seven soil samples were collected below the mulch layer to an average depth of 6 cm at evenly distributed locations in the rain gardens and used to determine antecedent soil moisture content and surface soil texture. Each sample was sealed in a pre-weighed, metal container and transferred to the laboratory within 8 h. Gravimetric moisture content (dry basis) was measured by placing each core in an oven at 105°C for 48 h (Dane and Topp, 2002). Three soil samples per garden were collected using a step soil probe to depth ranges of 7 to 39 cm, and these samples were used to determine soil texture. Because of the greater organic matter content and amended soils near the surface layer of the rain gardens, these deeper samples were obtained to evaluate a closer approximation of the *in situ* soil present before the rain garden was installed.

Bulk density was measured two to four times in each rain garden. Bulk density was determined by the core method using a standard sharpened steel cylinder to collect the soil sample, followed by laboratory measurement of mass and

volume (Dane and Topp, 2002). Three core samples per garden were taken for each measurement. The bulk density cores were taken from near the surface of the soil/mulch interface after the mulch was moved to provide a clean soil surface through which the cylinder could penetrate. Each measurement was taken following one of two conditions: (1) one to three days after the simulation, or (2) after a rainfall event larger than 0.25 cm (determined by a High Plains Regional Climate Center rain gauge located 0.4 km from the watershed), which is the rainfall amount typically necessary to produce runoff (USEPA, 2009). This was done to approximate a field capacity condition (Linsley and Franzini, 1972). Bulk densities obtained at non-field capacity conditions were adjusted to field capacity bulk densities for swelling soils based on the method used by Sharma (1989). Bulk density was measured to evaluate the physical characteristics of the surface soil and to allow conversion from gravimetric to volumetric moisture content.

Saturation volumetric water content was calculated for each site based on the assumption that this value is equivalent to porosity. The surface soil field capacity of each soil sample was calculated assuming that field capacity is 60% of porosity (Linn, 1994). Porosity was calculated using the bulk density and the percent organic carbon weighted-average particle density, which assumes mineral and organic particle densities of 2.65 and 1.25 g cm⁻³, respectively (Avnimelech et al., 2001). Dried samples at two depths (0-6 cm and 7-39 cm) were evaluated by Ward Laboratories, Inc. (Kearney, Neb.) for soil texture (USDA classification) and percent organic matter.

DATA ANALYSIS

All statistical analyses were performed in R 3.0.1 (R Core Team, 2013) with p-values less than or equal to 0.05 considered significant. Normality assumptions were tested using Shapiro-Wilk tests with critical p-values of 0.05, histograms, and visual observations of quantile-quantile plots. Specifically, the effects of surface soil type, cell size, ponding depth, and surface area to total catchment ratio were analyzed using the experimentally determined surface storage volume, drawdown rate, and drain time data. These tests were carried out using paired and lumped t-tests ($\alpha = 0.05$), as well as one-way analysis of variance, to evaluate the hypothesis of equal means between factors. Pearson correlation coefficients were calculated for each tested effect with an assumption of normality where appropriate. Nonparametric data were evaluated using Kruskal-Wallis analysis of variance and Wilcoxon signed-rank tests, where appropriate.

To eliminate transducer-related field noise in the surface area and storage volume curves (both with respect to time), drawdown data sets were plotted in SigmaPlot with nonlinear regression curves. The curves (power and exponential) generally had a coefficient of determination of 0.99. A stepwise water drawdown rate was calculated for all rain garden tests using transducer data filtered with a 2 min moving average smoother. For each simulator test, the slope of the linear fit of the time-series water head data was deemed the average “drawdown rate” for that test (fig. 8).

Figure 5. Rain garden total surface storage capacity versus WQV.

Figure 6. Total storage before overflow from WQV event versus full design WQV.

RESULTS AND DISCUSSION

STORAGE CHARACTERISTICS

None of the rain gardens evaluated had surface storage adequate to hold the WQV (fig. 5). Two sites were deemed “acceptable” because their total surface storage and infiltrated subsurface storage water (fig. 6) were within 10% of the WQV (Wardynski and Hunt, 2012). These sites (sites 1 and 11) retained 93% and 99% of the WQV, respectively, when both infiltration volume and surface storage volume were included. Considering both surface and subsurface storage, the other nine rain gardens performed well below the capacity needed to contain the WQV (table 2). Surface plus subsurface storage capacities ranged from 7% to 99% of the WQV, with a mean of 40% (SD = 32%). On average, 59% of the applied runoff infiltrated before overflow, 2.7 times more than surface storage, supporting the idea that surface storage as the sole sizing criteria is conservative (Jia et al., 2016). The surface plus subsurface storage volume was converted to an equivalent precipitation depth, assuming a runoff to rainfall ratio of 1, to compare to the WQV depth for Lincoln (3.0 cm). Site 11 managed to capture 2.99 cm of equivalent precipitation, but many sites captured far less, averaging 1.38 cm. Percentages of the WQV retained and equivalent precipitation were not calculated for site 4. The

elevation surveys of the high-water mark at the moment of overflow for site 4 were lost due to human error; however, this site was included in other analyses using the pressure transducer drawdown data and its surveyed stage-storage relationship.

PONDING DEPTH

Maximum ponding depth ranged from 7.6 to 12.4 cm, with a mean of only 10.1 cm (SD = 1.8 cm). Similarly, the average ponding depth was only 3.9 cm. (SD = 2.0 cm), reflecting that the rain gardens were not graded level (table 3). For a well-graded, level garden bed, the average ponding depth would be close to the maximum depth. This non-uniform grading reduced the potential water storage in all the rain gardens.

Design recommendations for ponding depth range from 8 to 61 cm, with 10 to 20 cm being typical. These depth guidelines assume a level bed and uniform mulch surface, which was not found in this study. The rain gardens examined were shallower than recommended by rain garden design guidelines, which limited their storage capacity.

Given the discrepancy between the rain gardens’ maximum and average ponding depths, a hypothetical extrapolation was performed to examine if a more uniformly graded

Table 3. Observed rain garden WQV depth before overflow and extrapolated storage assuming more uniformly graded surface.

Site	Maximum Ponding Depth (d_{max} , cm)	Average Ponding Depth (d_{avg} , cm)	Surface Storage Capacity (L)	d_{max} / d_{avg} Ratio	Surface Storage for Uniform Bottom at d_{max} (L)	WQV (L)	Extrapolated Volume Ratios	
							$V(d_{max}) / WQV$ (%) ^[a]	$V(d = 15.2 \text{ cm}) / WQV$ (%) ^[b]
1	10.1	3.4	306	2.97	909	1,569	58	87
3	8.2	3.1	127	2.67	339	1,484	23	42
4	12.4	7.7	640	1.61	1,031	1,852	56	68
5	10.5	3.5	152	3.00	453	2,531	18	26
6	8.0	2.9	75	2.76	207	2,388	9	16
7	8.4	2.8	91	3.00	273	750	36	66
8	7.6	1.8	228	4.22	963	1,062	91	181
9	11.1	2.8	182	3.96	722	1,679	43	59
10	11.6	2.4	179	4.83	865	2,078	42	55
11	11.8	5.6	393	2.11	828	1,762	47	61
12	11.7	7.1	585	1.65	964	2,499	39	50
Mean	10.1	3.9	269	3.00	687	1,787	42	65
SD	1.8	2.0	193.6	1.00	308	571	22	43

[a] Volume assuming depth of entire rain garden is graded at measured maximum ponding depth for each site.

[b] Volume assuming depth of entire rain garden is equal to 15.2 cm (minimum Nebraska rain garden recommendation).

rain garden with an average depth equivalent to the measured maximum depth could adequately store the WQV on the surface. Scaling up each site's surface storage capacity by the ratio of maximum to average ponding depth showed that the surface storage capacity would increase by an average of 3.9 times the measured value. However, only site 8, at 91%, had an extrapolated surface storage within 90% of the WQV (table 3). The extrapolated surface storage capacity averaged only 42% of the WQV. On average, the rain gardens would need more than double their extrapolated storage capacity to capture the WQV.

The range of maximum depths reported in table 3 (8.0 to 12.4 cm) is at the lower end of recommended rain garden depths (8 to 30 cm). Assuming a uniformly graded garden, a further extrapolation was assessed by assuming a depth for all gardens equal to 15.2 cm. A depth of 15.2 cm was chosen because it represents the average recommended depth in the Nebraska Cooperative Extension rain garden manual (Franti and Rodie, 2013). Even with this depth extrapolation, the gardens stored, on average, only 65% of the WQV, and only one garden (site 8) had storage adequate to hold the WQV on the surface (table 3). Simply grading the gardens evenly at greater depth would not achieve the WQV storage goals; expanding the basin storage area would also be needed.

Published rain garden design guides vary in their recommended ratios of catchment area to basin plan view area, suggesting that rain garden areas be anywhere from 3% to 43% of the catchment area depending on distance from the home, soil type, and infiltration rate (Bannerman and Considine, 2003; Austin, 2013; Franti and Rodie, 2013; Oregon, 2013; NCCE, 2014), with the most common range being 3% to 10%. The garden-to-catchment ratios observed in this study ranged from 6% to 25%, within the range of previously reported studies and design recommendations. Therefore, it appears that ponding depth, not surface area, better explains the inability of most studied systems to retain the entire WQV.

SOIL PROPERTIES

Surface soil texture (0 to 6 cm depth) for ten of the eleven rain gardens assessed was a loam (table 4). As expected, the underlying soil profile (7 to 39 cm) showed greater clay content than the surface soils ($p < 0.001$), with a mean of 36% (SD = 3.3%). The predominant classifications of these underlying soils were silty clay loam and clay loam (seven and three gardens, respectively). This layer is likely the limiting

layer in rain garden performance because of the low infiltration capacity (Huwe, 2010). Clay content values of 5% to 12% are reported in the literature as the maximum desired values for bioretention media mixtures (PGCo, 1999; Hunt et al., 2006). Compared to bioretention, all rain gardens in this study exceeded the recommended clay and silt contents. Organic matter was significantly greater in the 0 to 6 cm surface layer ($p = 0.003$) than in the subsurface due to organic amendments during construction and/or increased biological activity at the surface. Surface organic content showed a moderately positive correlation with the percentage of the total WQV captured by the rain gardens ($r = 0.582$, $p = 0.077$).

Bulk density (dry basis) of the amended surface soil ranged from 0.56 to 1.11 g cm⁻³ with a mean of 0.88 g cm⁻³ (SD = 0.16 g cm⁻³). After applying a linear regression statistical analysis, a slight negative correlation was found between bulk density and drawdown rate ($r = -0.457$). All bulk density values were lower than the critical bulk density value of 1.4 g cm⁻³ defined by Jones (1983) as the density at which plant penetration is likely to be severely restricted. Organic matter, which has a lower particle density (1.25 g cm⁻³), is thought to aid in lowering bulk density in the surface layer.

June 2011, when six of the eleven evaluations were performed, was a wetter than average June for Lincoln, Nebraska. As recorded by the High Plains Regional Climate Center weather station near the watershed, June 2011 experienced 17.0 cm of rain, which is 54% greater than average (table 5). July 2011 was drier than average, with a 24% decrease from the normal monthly total of 6.9 cm. Regardless of rainfall totals, the surface soil antecedent moisture was frequently above field capacity (table 5). High surface soil moisture conditions can partly be explained by studies that show greater soil water content when more compost and organic matter are present (Carpenter, 2010). The extensive mulch layers observed on the surface of each rain garden may have served three functions: (1) to soak up influent runoff and rainwater within the mulch material void spaces, (2) to help keep the soil moisture capacity greater than would be observed under bare soil conditions when evapotranspiration (ET) would be greater (Chung and Horton, 1987; Diaz and Jimenez, 2005), and (3) to help protect the underlying soil from compaction effects from the force of raindrop impacts (Hillel, 1998; Assouline, 2004), which theoretically should result in higher soil conductivity beneath the mulch.

Table 4. Measured soil characteristics.^[a]

Site	Rain Garden Amended Surface Soil (0 to 6 cm)						Subsoil (7 to 39 cm)				
	Sand (%)	Silt (%)	Clay (%)	USDA Texture	OM (%)	BD (g cm ⁻³)	Sand (%)	Silt (%)	Clay (%)	USDA Texture	OM (%)
1	41	38	21	L	7.3	0.95	18	46	36	SCL	2.1
3	38	37	25	L	4.8	1.11	26	38	36	CL	1.2
4	34	41	25	L	5.3	0.87	24	40	36	CL	1.3
5	37	46	17	L	9.3	0.93	22	40	38	CL	1.5
6	48	35	17	L	8.4	0.56	14	50	36	SCL	2.5
7	44	37	19	L	7.4	0.89	20	42	38	SCL	1.8
8	36	37	27	L	6.5	0.74	20	42	38	CL	1.9
9	32	43	25	L	4.1	1.10	24	48	28	CL	2.8
10	26	46	28	L	6.2	1.11	-	-	-	-	-
11	28	50	22	SL	25.3	0.92	12	46	42	SC	2.1
12	32	38	30	CL	6.4	0.77	26	38	36	CL	1.1
Mean	36	41	23		8.3	0.90	21	43	36		1.8
SD	6.6	4.9	4.4		5.8	0.17	4.8	4.2	3.5		0.6

[a] L = loam, SL = silty loam, CL = clay loam, SCL = silty clay loam, SC = silty clay, OM = organic matter, and BD = bulk density.

Table 5. Precipitation and soil moisture of rain gardens.

Site	Date of Simulation (2011)	Last Rain Event before Simulation (days)	Last Rain Event Depth (cm)	Measured Antecedent Moisture Content at Surface (0 to 6 cm)		Estimated Moisture Content	
				Gravimetric (g g ⁻¹)	Volumetric (cm ³ cm ⁻³)	Saturation (cm ³ cm ⁻³)	Field Capacity (cm ³ cm ⁻³)
1	June 6	6.3	1.40	0.51	0.49	0.63	0.38
3	June 14	5.3	2.03	0.33	0.37	0.57	0.34
4	June 20	2.1	3.25	0.48	0.49	0.66	0.40
5	June 23	1.9	1.88	0.45	0.42	0.63	0.38
6	June 28	1.3	6.32	0.85	0.48	0.78	0.47
7	June 30	3.3	6.32	0.56	0.50	0.65	0.39
8	July 14	6.9	1.24	0.64	0.47	0.71	0.43
9	July 11	3.9	1.24	0.31	0.34	0.58	0.35
10	July 26	18.9	1.24	0.46	0.51	0.57	0.41
11	July 27	0.04	0.33	0.46	0.40	0.60	0.36
12	July 21	13.9	1.24	0.44	0.36	0.70	0.42
Mean				0.50	0.44	0.64	0.39
SD				0.15	0.06	0.07	0.04

DRAWDOWN RATE

The rain garden WQV simulations yielded average drawdown rates ranging from 1.2 to 85 cm h⁻¹. These rates exceed the benchmark percolation rates recommended by multiple rain garden design guides (fig. 7). The median drawdown rate for event 2, the overflow event, was 2.6 cm h⁻¹, which was lower than the median drawdown rate for event 1, the WQV event, at 4.1 cm h⁻¹. Average drawdown rates for event 1 from all eleven rain gardens met or exceeded the Nebraska rain garden design recommendation of 0.64 cm h⁻¹, and only site 11 drained at a slower rate than 0.64 cm h⁻¹ for event 2 (Franti and Rodie, 2013). For event 1, the entire interquartile range (25th to 75th percentiles) of the data was above the percolation rate values presented in three rain garden design manuals, which ranged between 0.5 and 1.6 cm h⁻¹ (Bannerman and Considine, 2003; Franti and Rodie, 2013; NCCE, 2014). Only the North Carolina bioretention guideline's minimum infiltration rates were near the median drawdown rates found in this study. The North Carolina guidance is based predominately on coarse sandy engineered media and underdrain infrastructure. Our drawdown performance measured in select homeowner rain gardens without

underdrains, out-performed the North Carolina guidance criteria.

The drawdown rate within each site generally followed a decreasing trend, with the greatest rate at the beginning of the drainage period and evolving into a pseudo steady-state linear decrease in head, as expected in soil-based drainage systems. Average drawdown rates were computed from linear fitting of the more steady-state portion of the event drawdown curve (fig. 8). Unlike Lucke et al. (2015), who found that drier bioretention cells stored higher volumes of water during testing, no significant correlations were found in this study between antecedent soil moisture and percentage of the WQV stored subsurface, stored on the surface, or in combined subsurface and surface storage. However, the minimum drawdown rates (i.e., the rates at which the decrease in surface ponding over time begins to asymptote) for the WQV of each site showed a strong negative correlation ($r = -0.722$; $p = 0.012$) with initial soil moisture (fig. 9). This relationship has been identified in the literature because infiltration rates are lower for wet soil than for dry soil (Ward and Trimble, 2003). The overflow event drawdown rate was also correlated with antecedent moisture content ($r = -0.618$;

Figure 7. Average drawdown rates for two simulated events (WQV and overflow event) at ten sites (data are missing for site 4).

Figure 8. Example of a linear fit of ponded head over time after applying a volume equivalent to 3 times the WQV to examine overflow characteristics (event 2) at site 11. The slope of the fit represents this site's average drawdown rate in cm min^{-1} .

$p = 0.024$); however, because only the WQV event had a measured antecedent moisture, the correlation does not relate to anything physically based for the overflow event.

The rain gardens evaluated in June had greater initial soil moisture contents compared to the July events, likely due to above-average precipitation for June (150% of normal). July experienced below-average precipitation (75% of normal); however, the soil moisture content of the surface soils of the rain gardens evaluated in July were not statistically different from the June data ($p = 0.89$). The two sites where the greatest drawdown rates were measured (sites 9 and 11) were also characterized by the lowest and fourth lowest initial soil moisture values (0.34 and $0.40 \text{ cm}^3 \text{ cm}^{-3}$, respectively). The presence of clay shrinkage-related cracks combined with lower antecedent soil moisture likely contributed to greater drawdown rates. Generalizations on specific measured initial soil moisture with regard to drawdown rate should be

Figure 9. Scatterplot of measured antecedent soil moisture before the runoff simulations and the minimum infiltration rates for both the WQV event and the overflow event.

made carefully because the moisture content was measured only in the surface of the amended layer. The subsoil initial moisture content is also related to drawdown rate but was not measured in this study to minimize disturbance of the rain garden surface.

DRAIN TIME

The mean drain times for the WQV event and the overflow event were 1.8 h ($\text{SD} = 1.8 \text{ h}$) and 5.5 h ($\text{SD} = 8.9 \text{ h}$), respectively, with a maximum time recorded of 30 h (table 6). Drain times for all events were less than the 48 h maximum drain time recommended for bioretention systems (USEPA, 1999; Bannerman and Considine, 2003).

The average maximum ponding depth among all sites was 10.1 cm , which is less than the recommended rain garden depth in Nebraska of 15.2 to 30.5 cm (Franti and Rodie, 2013). To examine drain time with a standard depth, drain times for all events were extrapolated assuming an evenly graded storage depth of 15.2 cm and using the measured minimum drawdown rate (table 6). The resulting extrapolated mean drain times were 16.9 and 14.3 h for events 1 and 2, respectively, and were greater by a factor of approximately 3 to 10 than the observed drain times of 1.8 and 5.5 h , respectively. These average extrapolated values were still below the 48 h maximum threshold recommended by the Nebraska Cooperative Extension rain garden guide, with the exception of site 4 (fig. 10). The mean extrapolated drain time was greater for event 1 than for event 2, the opposite relationship as the observed drain time. This is because of the high variability of the minimum drawdown rate between events 1 and 2, and evaluating the extrapolated events at the same starting depth.

OVERFLOW STRUCTURE

Rain garden overflow structures are meant to be placed at an elevation to ensure that weir-like overflow occurs when the ponded zone is full of water. Most of the evaluated rain gardens had poorly designed or constructed overflow structures that may have contributed to their inability to store the WQV. Overflow structure design flaws included:

- Poor grading resulting in the outflow structure not being the lowest elevation of the berm.

Table 6. Observed and extrapolated drain times using observed minimum drawdown rates.

Site	Minimum Observed Drawdown Rate (cm h^{-1})		Observed Drain Time (h)		Extrapolated Drain Time for 15.2 cm Depth (h)	
	Event 1	Event 2	Event 1	Event 2	Event 1	Event 2
1	4.1	3.4	2.1	2.6	3.7	4.4
3	28	45	0.2	0.4	0.5	0.3
4	0.18	0.2	6.4	30	84.4	76
5	5	3.9	1	1.3	3.1	3.9
6	0.4	1.7	1.5	1.8	40	9.1
7	1.4	1	3.4	4.9	11.1	14.8
8	3.7	0.9	1.8	12.9	4.2	16.9
9	67.8	18.3	0.1	0.6	0.2	0.8
10	0.4	0.65	2	5	38	23.4
11	70.4	12.7	0.2	0.6	0.2	1.2
12	16.2	2.38	0.6	0.8	0.9	6.4
Mean	18	8.2	1.8	5.5	16.9	14.3
SD	26.7	13.5	1.8	8.9	26.8	21.8

Figure 10. Comparison of measured drain times for the WQV event and the overflow event (black). White data points show extrapolated drain times assuming the measured minimum drawdown rate and a garden graded at 15.2 cm. The gray region indicates drain times greater than or equal to the maximum recommended 48 h drain time (Franti and Rodie, 2013).

- Lack of an overflow structure.
- Lack of adequate rock or erosion control at the overflow structure.
- Inadequate width of the outflow weir to pass larger flows before widespread overtopping of the berm occurs.

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

Two rain gardens (sites 4 and 8) did not have observable overflow structures. However, both sites were observed to have one distinct preferential location over which water flowed during the overflow storm. Both berms were populated with turf grass. From an erosion control standpoint, this grass may have been beneficial, as it prevented mulch and soil from overtopping the berm; however, excessive grass on the berm can migrate and spread into the rain garden, possibly disrupting the plant population. It should be noted that site 8 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 with plastic and sandbags to simulate drainless conditions, allowing the researchers to observe overflow of the grass berm.

To some degree, every site had a large amount of mulch that floated during the simulation. Most sites had mulch that appeared to have been shredded, although it was not double- or triple-shredded, a common mulch specification in the

mid-Atlantic (NCDEQ, 2017). The larger, long woodchips were prone to floating during the simulation. This mulch slowly migrated to the overflow structure (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, mulch export was observed, most notably at sites 5 and 6.

SUMMARY AND CONCLUSIONS

This study evaluated the event-based hydrologic performance parameters of eleven established residential rain gardens in Lincoln, Nebraska, two to four years after installation. On average, the rain gardens retained only 40% (SD = 32%) of their WQV resulting from the 3.0 cm WQV rainfall. On average, only 16% (SD = 9%) of the water volume retained was held as surface storage, whereas many guidance sources cited herein recommend designing rain gardens to capture 100% of the WQV as surface storage. An average of 59% (SD = 16%) of water applied to the rain gardens was stored as subsurface storage, with only three sites having less than 50% as subsurface storage. The bulk of the stored water was accounted for as subsurface storage because of infiltration, suggesting that soil water storage is an important process when native and amended soils are adequately permeable (Roy-Poirier et al., 2015). When surface and subsurface storage is included, only two rain gardens stored a volume within 90% of the WQV.

This study shows that drawdown rate and drain time for eleven established rain gardens in Lincoln, Nebraska, are not the limiting factors for rain garden performance. Both the average surface storage depth and the rain garden storage area were undersized to contain the WQV storm event. The average maximum storage depth of 10.1 cm across all gardens was less than the 15.2 cm rain garden depth recom-

mended in Nebraska. In addition, the rain gardens were not graded evenly to maximize surface storage, and shallow areas were prevalent that reduced surface storage. An extrapolated surface storage volume was calculated based on extrapolating the maximum depth of each garden over a uniformly graded surface. In this case, rain gardens graded only to their measured maximum depth generally stored less than half (42%) of the WQV, indicating that deeper storage depths would be required. Deeper rain gardens require more soil disposal, require more time and labor, and may not integrate as fluidly with existing landscapes, but they could capture more runoff compared to shallower systems. There may be safety issues associated with digging too deeply on private property (e.g., buried utilities) as well as the risk of creating a habitat for mosquito breeding. For these reasons, adequate storage may be best obtained by expanding the basin area for a given depth to provide adequate storage for the WQV.

Drain times and drawdown rates met common design guidelines for homeowner systems. The mean drain time was 1.8 h for the WQV storm (3.0 cm rainfall) and 5.5 h for the overflow simulation (3 times the WQV). With only one rain garden draining longer than 24 h (30 h), these established systems without engineered underdrains were able to meet the 48 h upper limit for drain time commonly found in the literature (IDALS, 2009; Franti and Rodie, 2013; NCCE, 2014).

The compost-amended surface soils (0 to 6 cm) had relatively low bulk densities (0.65 to 1.11 g cm⁻³) and significantly greater organic matter content than the subsoils, which had a greater clay content than the surface soils. The percent organic matter in the surface soils had a moderately positive correlation with the percentage of the WQV retained. Bulk density of the surface soil was slightly negatively correlated to average drawdown rate, with less dense soil allowing more rapid stormwater conductivity. Initial soil moisture also played a role in rain garden performance, showing a strong negative correlation with measured minimum drawdown rates.

As with surface storage, we extrapolated the drain times for each rain garden based on a uniformly graded, 15.2 cm deep rain garden basin to evaluate drain times for systems with more adequate surface storage. Only one rain garden had an extrapolated drain time greater than 48 h. While the drawdown rates and drain times satisfied design guidelines, the surveyed bottom topography of the rain garden basins and the overflow structures were highly variable. Frequently, areas within the rain garden surface were never fully inundated or wet, rendering them underused as storage volume before overflow occurred. Highly variable construction grading has been identified as a performance issue in larger bioretention systems (Wardynski and Hunt, 2012). When overflow occurred, it often did not flow over the established overflow structures, and some overflow structures received no water flow. Often, several locations along the berms were overflowing. Future efforts to properly size and grade basins and improve the placement of overflow structures will increase the water storage capacity, pollutant removal, and erosion prevention of residential rain gardens.

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