12-2011

Hydrologic Evaluation of Established Rain Gardens in Lincoln, Nebraska Using a Storm Runoff Simulator

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Anderson, Andrew R., "Hydrologic Evaluation of Established Rain Gardens in Lincoln, Nebraska Using a Storm Runoff Simulator" (2011). *Environmental Engineering Theses and Graduate Student Research*. 5.
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HYDROLOGIC EVALUATION OF ESTABLISHED RAIN GARDENS IN LINCOLN, NEBRASKA USING A STORM RUNOFF SIMULATOR

by

Andrew R. Anderson

A THESIS

Presented to the Faculty of

The Graduate College at the University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Master of Science

Major: Environmental Engineering

Under the Supervision of Professor Thomas G. Franti

Lincoln, NE

December 2011

HYDROLOGIC EVALUATION OF ESTABLISHED RAIN GARDENS IN LINCOLN, NE

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University of Nebraska, 2011

Advisor: Thomas G. Franti

Increased urbanization has resulted in water quality and flooding problems for many receiving waters in the United States. Bioretention, or rain gardens, is one of the most widely popular and effective best management practices in low impact development (LID), which strives to return a watershed to a predevelopment hydrologic regime. Many studies have evaluated large 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. Additionally, few studies address rain garden performance in cold, arid, or semi-arid climates found in the Midwest U.S. The objective of this project was to evaluate the hydrologic properties of twelve established residential rain gardens using a stormwater runoff simulator. A volume-based design storm of 1.19 inches (90% Water Quality Volume) was applied as a synthetic SCS-Type II 30-minute runoff hydrograph in each garden based on their respective catchment characteristics. Data including ponding zone storage capacity, infiltration rate, drain time, soil characterization, and observations of berm, outflow, and grading performance were collected and analyzed to make performance conclusions for each site. Results indicate that rain gardens constructed on loamy to silty clay loam soils in a residential watershed in Lincoln, NE can infiltrate at the rates recommended by state and national guidelines. The geometric mean infiltration rate for all sites was 4.13

cm h^{-1} and 2.75 cm h^{-1} for the design event and overflow event, respectively. Every rain garden tested drained in 30 h or less, with six gardens draining in less than one hour. Rain garden storage capacity was poor with only two gardens able to hold the water quality design runoff volume. On average, rain gardens studied were able to hold only 40% of the design storm volume. Poor basin grading, outflow structure construction and placement, and berm integrity are reasons for the inadequate storage.

Acknowledgements and Grant Information

My time as a master’s student at UNL was enjoyable and rewarding thanks to the dedication of my graduate advisor Dr. Franti. He taught me to look at a problem from every angle and to think critically. Much gratitude is also owed to advisory committee members Dave Shelton and Dr. Dean Eisenhauer, who brought unique perspectives to my graduate work.

None of my research would have been possible without the time, labor, and input knowledge dedicated by research engineer Mr. Alan Boldt. He put up with my initial learning curve and stubbornness, giving me great ideas along the way.

Many thanks are deserved by agricultural engineering graduate student Daniel Tucker for putting in some long hours and coming in early over the course of his first summer in Nebraska. I could not have successfully completed the project goals without his second set of eyes and extra hands. Michael McKinney and Matthew Wold, two other graduate students in agricultural and biological systems engineering, helped me set up the simulator equipment for multiple rain garden evaluations this summer. These folks deserve a “thank you” for taking time out of their schedule to assist me in and out of the office.

I could not have gotten through the stressful moments of graduate school without my dedicated girlfriend Cassie. She continually supported me and reassured me when classes and research seemed to weigh heavily on me. She was also instrumental in tirelessly reviewing my thesis during the course of its completion.

I would like to thank the funders of my research project, the United States Department of Agriculture-National Institute of Food and Agriculture (USDA-NIFA).

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Chapter 1 – Introduction

Urban stormwater runoff is a major factor contributing to impairment of water bodies in the United States (US EPA, 2004). This can be partially attributed to increased urban development. As land becomes urbanized, the percent of impervious land typically increases. Impervious cover does not allow infiltration to occur, with precipitation that normally infiltrates instead becoming overland runoff. Less infiltration results in decreased groundwater recharge and lower stream base flows (Ferguson and Suckling, 1990) as well as a substantially greater proportion of overland flow relative to precipitation. Problems associated with increased runoff volume include erosion and flooding.

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, 2002).

Increased urbanization has also been shown to negatively impact water quality. Higher pollutant loads in stormwater containing heavy metals, nutrients, pesticides, sediment, and pathogens are associated with impervious land development and are factors in physical and biological impairments. Schueler (1994) reported that noticeable declines in ecosystem health occur once the percentage of impervious cover exceeds 20% in a watershed. In response to these problems, Congress amended the Clean Water Act to require municipalities discharging stormwater to regulate it as a point source. The United States Environmental Protection Agency introduced the National Pollutant Discharge Elimination System

(NPDES) with this authority. Municipalities governed under NPDES are required to either reduce storm water pollutant loadings to the “maximum extent practicable” or to implement best management practices (BMPs). In 1999, Prince George’s County, Maryland integrated these 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).

While traditional stormwater management primarily focuses on reducing peak flows, LID additionally focuses on volume reduction through various BMPs. BMPs can either be non-structural or structural. Non-structural BMPs include maintenance programs, housekeeping and disposal practices, such as street sweeping, outreach initiatives, and land-use planning strategies (Novotny, 2003; Roy-Poirier et al., 2010). Structural practices include rainwater harvesting systems, green roofs, pervious concrete, bioswales and bioretention, constructed wetlands, and other engineered water quality treatment devices. All of these measures have the goal of reducing the “effective impervious area” in the catchment by disconnecting runoff from impervious surfaces that would reach receiving water bodies (Booth and Jackson, 1997). Since the development of LID practices and programs more than a decade ago, much research has been done around the country to improve the effectiveness of various BMPs. Their increased effectiveness, low impact, and high aesthetic value make them increasingly more attractive to municipalities (Asleson et al., 2009).

A specific structural BMP viewed as effective for volume reduction is bioretention. A bioretention system consists of a small area of excavated soil backfilled with a mixture of high-permeability soil and organic matter for the purpose of increasing infiltration. Unlike traditional detention basins, they take an ecosystem approach where native terrestrial vegetation creates a deep root zone designed to maximize infiltration volume (Roy-Poirier et al., 2010). These systems usually contain engineered media, with an option for an under-drain piping system below the sand layer when native soils are not hydraulically conductive enough to promote groundwater recharge (Rusciano and Obropta, 2007). In the state of Nebraska, systems without an under-drain are referred to as rain gardens. These systems rely on deep root growth to open up subsoil layers to promote infiltration. Two layers, the ponding zone and the engineered soil media, combine to create a system that can reduce stormwater volume and retain and treat contaminated stormwater. Research has shown bioretention has high potential in pollutant removal for total suspended solids (TSS), phosphorus, nitrogen, heavy metals, oil and grease, and bacteria (Davis, 2001; Dietz and Clausen, 2005; Hunt et al., 2006; Li and Davis, 2009).

Past research into the hydrologic impacts of bioretention has also been conducted, both with column studies and field studies. Studies done at the University of Maryland have shown significant reductions in storm water outflow volumes from bioretention cells in urban areas (Davis, 2008). Smaller storm events were almost entirely retained with zero out flow. Hunt et al. (2006) showed similar results in field scale bioretention cells. His study also demonstrated the increased ability of bioretention to mitigate runoff volumes in the summer when compared to winter months (0.07 and 0.54 outflow-to-runoff volume ratios, respectively).

Rain gardens contain some unique structural features. Rain garden plants are selected based on their ability to function during saturated conditions that may last 24-48 hours, yet still thrive during extended dry periods. In Nebraska, there are a variety of perennials, grasses, and shrub species adapted to different climate regions in the state (Rodie et al., 2007). A layer of mulch is added to enhance solid retention, reduce clogging of surface soil by eroded fine particles, and minimize rain garden soil erosion. An inlet structure directs flow from rooftop downspouts, overland flow, or a combination of both. An overflow structure bypasses flows above the surface storage capacity of the unit. Under-drain systems are common in bioretention cells that have low-permeability soils in order to prevent standing water for long periods of time. Figure 1 shows the typical appearance of a rain garden in Nebraska with native plants, a downspout inlet, and engineered soil with a mulch layer. Figure 2 illustrates the layers of a rain garden below the soil. The goal is to create a retention and filtration zone from which water can then recharge groundwater.

Bioretention is seen as a cost-effective way to mitigate stormwater volume and pollutant loadings. It is one of the most cost-effective post-development structural BMPs in LID. As such, Nebraska has implemented rain garden programs to improve water quality and comply with a total maximum daily load (TMDL) in the Holmes Lake watershed in Lincoln, Nebraska (NDEQ, 2003).

Figure 1. Photograph of a typical rain garden in Nebraska. (Courtesy of City of Lincoln)

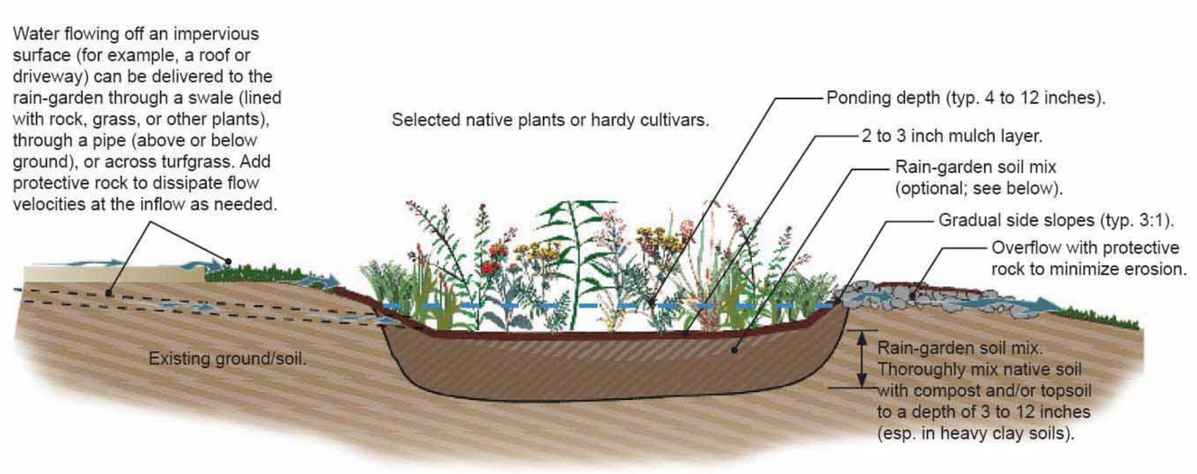

Figure 2. Cross section of rain garden (no under-drain system).

STUDY WATERSHED

Holmes Lake is a 45.3 hectare (111.9 acre) flood control reservoir in southeast Lincoln, Nebraska (Figure 3).The Nebraska Department of Environmental Quality (NDEQ) has assigned to Holmes Lake various designated uses, including flood control, primary contact recreation, aquatic life warmwater class A, agriculture water supply class A and aesthetics (NDEQ 2000). The 1,400 hectare (3,460 acre) watershed drains into three tributaries, the most prominent of which is Antelope Creek, a moderately urbanized channel. The watershed land use is characterized by residential development with some commercial development. The dominant soil type in the watershed (35% by area) is Aksarben silty clay loam (NRCS Web Soil Survey, 2011), which is classified as an NRCS Hydrologic Soil Group C soil. 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).

NDEQ added Holmes Lake to the state's 1998 Section 303(d) impaired waters list for atrazine, arsenic, nutrients, dissolved oxygen and sedimentation (US EPA, 2011). While atrazine and arsenic were removed from the list in 1999, sedimentation, dissolved oxygen, and nutrients remained listed pollutants. This led NDEQ to develop a total maximum daily load (TMDL) for phosphorus and sediment in 2003, calling for 53 percent reduction in sediment and 97 percent reduction in phosphorus (NDEQ, 2003).

In 2005 the City of Lincoln completed a lake restoration that primarily involved dredging the sediment from the lake bottom to improve aquatic habitat and restore storage volume. Other structural measures included stream and wetland restorations and stream

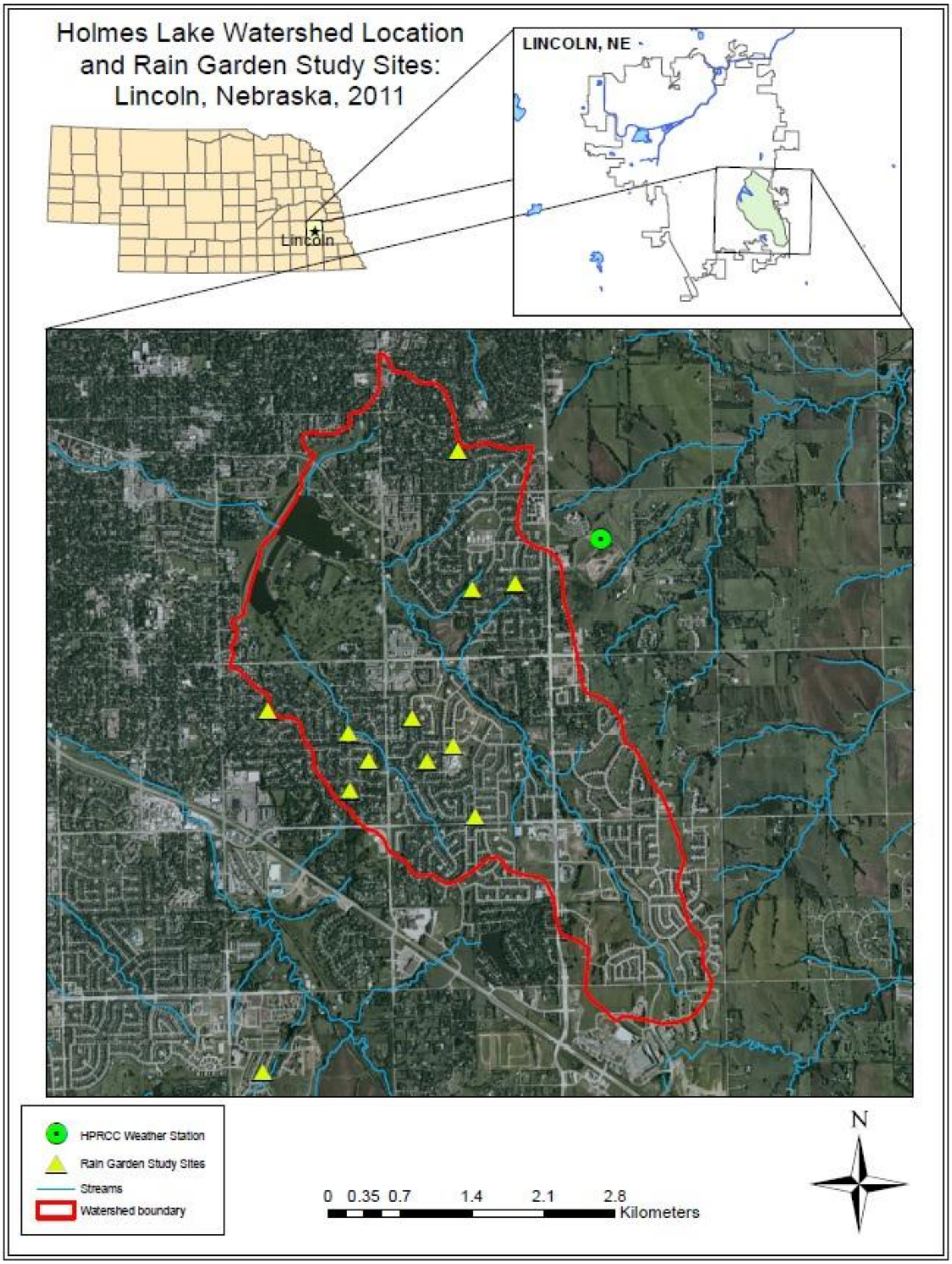

Figure 3. Map showing location of Holmes Lake Watershed in southeast Lincoln, Nebraska in Lancaster County (ESRI, 2010)

stabilization of Antelope Creek. Education, outreach measures, and demonstration projects aimed at reducing phosphorous and sediment loading into the lake were implemented.

In June 2007 the City of Lincoln initiated the Holmes Lake Watershed Improvement Program focused on pilot programs with incentives for citizens who were interested in obtaining rain gardens, rain barrels, and free 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.

The rain garden program was introduced at a public meeting in 2007, where citizens living in the Holmes Lake watershed could apply for subsidized rain garden installations. Out of 55 applications, 17 homeowners were chosen. These original rain gardens constitute the oldest rain gardens in the City associated with the Holmes Lake Water Quality Improvement Program. They were all installed by Campbell's Nursery in Lincoln, NE, which had a contract with the city for all rain garden installations associated with the Holmes Lake restoration. Nine sites for this study were chosen from this pool of original rain gardens built in 2007, located within the Holmes Lake watershed boundary. In 2008 and 2009, the rain garden incentive program was expanded citywide; resulting in 76 homeowner installations around the city (Meder, 2009). Two sites for this project were chosen from these 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 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). The simulator has progressed from a gravity flow hydrograph simulator to a prototype sediment mixer and delivery system. The prototype system (Alms et al., 2011) was used as a water delivery system in this study for residential rain garden evaluation.

SIMULATOR MODIFICATION FOR RAIN GARDEN STUDY

The simulator developed by Alms et al. (2011) used an 1890 L (500 gal) conical bottom tank, a 0.373 kW (0.5 hp) impeller mixer, and a 4.85 kW (6.5 hp), 7.6 cm (3 in.) Hypro® centrifugal trash pump in a recirculation line to achieve uniform sediment concentrations. The calibration, validation and operation control was achieved using a McCromter full bore magnetic flow meter, an A-T Controls V-port control valve, a National Instruments Compact Data Acquisition System, and a control program written in National Instruments LabVIEW^{TM} 8.2 (LabVIEW, 2006).

All components and equipment used by Alms et al. (2011), with the exception of the trash pumps and Y-strainers, were used in a trailer-tank system that could be driven to a residential rain garden and safely parked on the street (Figure 4). Because there was no longer a sediment criteria, the flow schematic could be simplified (Figure 5).

A new trash pump provided hydraulic pressure during the experiments. The pump allowed for consistent head, and maintained the high flow rates needed to deliver the overflow storm. New 7.62 cm (3 in.) diameter, 15.2 m (50 ft) white vacuum hose was used to convey the water from the hose setup on the tank bed to the inlet of the rain gardens. For this study, the impellor served the function of baffling potential vortexes formed in the conical tank. This was critical to pump performance, as any air pockets present in the pump could prevent the necessary vacuum from forming, in which case the pump cannot draw water (Industrial Quick Search® Manufacturer Directory, 2011). A 120-V generator powered the pump, impellor, and control program equipment.

Figure 4. Runoff simulator at site 3. Large image shows water supply tank, trash pump, and trailer hose configuration. Smaller insert image shows magnetic flow meter (blue), control valve (red), and plumbing making up the delivery system at the rain garden inlet.

PROJECT OBJECTIVES

This project involved using a runoff simulator to evaluate the hydrologic characteristics of residential rain gardens. 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:

1. Evaluate design features, including:
    a. In-situ storage depth and volume
    b. Outflow structure and function
    c. Infiltration rate
    d. Soil profile characteristics
2. Recommend design changes in each rain garden (depth, area, berm, grading, appropriate drainage)

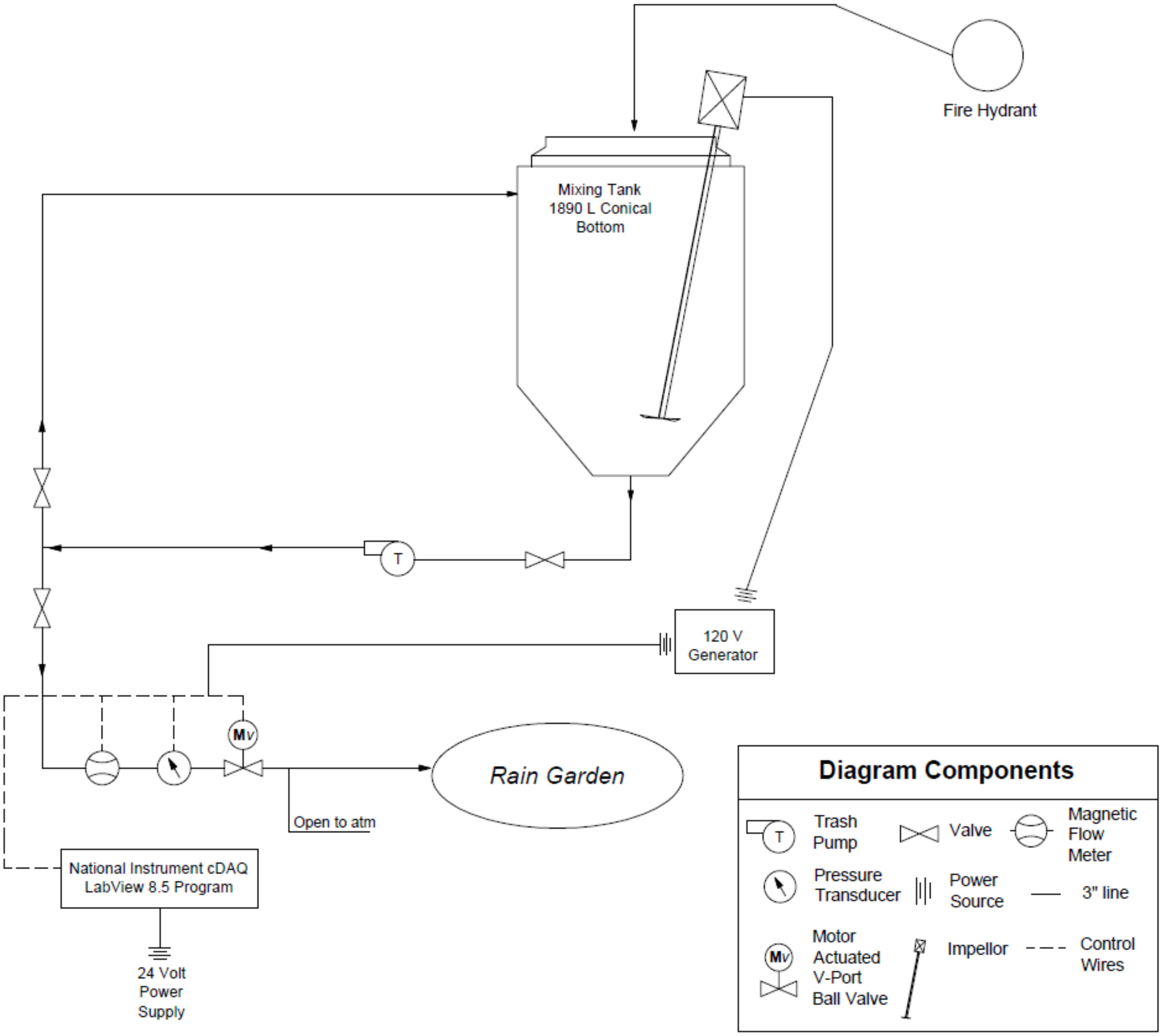

Figure 5. Schematic of flow system used in this study to evaluate residential rain gardens.

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Chapter 2 – Hydrologic Evaluation of Established Rain Gardens in Lincoln, Nebraska

ABSTRACT

Increased urbanization has resulted in water quality and flooding problems for many receiving waters in the United States. Bioretention, or rain gardens, is one of the most widely popular and effective best management practices in low impact development (LID), which strives to return a watershed to a predevelopment hydrologic regime. Many studies have evaluated large 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. Additionally, few studies address rain garden performance in cold, arid, or semi-arid climates found in the Midwest U.S. The objective of this project was to evaluate the hydrologic properties of twelve established residential rain gardens using a stormwater runoff simulator. A volume-based design storm of 1.19 inches (90% Water Quality Volume) was applied as a synthetic SCS-Type II 30-minute runoff hydrograph in each garden based on their respective catchment characteristics. Data including ponding zone storage capacity, infiltration rate, drain time, soil characterization, and observations of berm, outflow, and grading performance were collected and analyzed to make performance conclusions for each site. Results indicate that rain gardens constructed on loamy to silty clay loam soils in a residential area of Lincoln, NE infiltrate at the rates recommended by state and national guidelines. The geometric mean infiltration rate for all sites for the first simulated runoff test was 4.13 cm h^{-1} and 2.75 cm h^{-1} for the design event and overflow event, respectively. Every rain garden tested drained in 30 h or less, with six gardens draining in less than one hour. Rain garden storage capacity was poor with only two gardens able to

hold the water quality design runoff volume. On average, rain gardens studied were able to hold only 40% of the design storm volume. Poor basin grading, outflow structure construction and placement, and berm integrity are reasons for the inadequate storage.

LITERATURE REVIEW

In the last two decades, low impact development (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). One particularly effective best management practice (BMP) used to accomplish LID objectives is bioretention. Research on water quality and hydrologic characteristics of bioretention systems has been progressing since Prince George's County, Maryland pioneered the concept in 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, typically residential-scale rain garden cells without under drain systems that rely solely on percolation into native soil as the mechanism for outflow reduction. 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 et al., 2009; Grewal et al. 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 (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 obtain replicates (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 rather than highly variable soil infiltration tests at different 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) and a study by the US EPA (2000) used synthetic runoff to study rain gardens in Maryland. Both of these studies 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.

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:

1. Evaluate design features, including:
    a. In-situ storage depth and volume
    b. Outflow structure and function
    c. Infiltration rate
    d. Soil profile characteristics
2. Recommend design changes in each rain garden (depth, area, berm, grading, appropriate).

MATERIALS AND METHODS

The control system and runoff simulator developed by Franti et al. (2007a; 2007b) and Alms et al. (2011) was modified to meet the following criteria:

1. Portable and mobile in residential areas
2. Functional without interfering with neighborhood traffic and safety
3. Able to convey necessary volume of water to residential rain garden inlet

Portability was accomplished by arranging the simulator equipment on a 5.5 m by 2.4 m (18 ft by 7.9 ft) flatbed trailer. The City of Lincoln Water System fire hydrants were used as a water supply. Fire hydrants were within 300 ft of each site studied.

BUMP signs were rented from All Roads Barricades, Inc. for sites that required crossing streets with hose from the fire hydrant. Street-crossing posed a risk of initiating a water hammer in the line caused by vehicle traffic, so a customized wooden hose-protection structure was constructed to prevent this.

SITE SELECTION

Around fifty rain gardens built since 2007 were visited in the spring of 2011 to make visual observations and to assess the compatibility of the gardens to the study. The oldest rain gardens (constructed in2007) were prioritized to observe hydrologic effects of established plant and soil biotic communities. The characterization of the plant species in rain gardens in the Holmes Lake watershed is discussed elsewhere (Liebsch, 2011). Twelve rain gardens were selected for evaluation. Eight of these gardens were constructed in 2007, three were constructed in 2008, and one was constructed in 2009. Of the seventeen constructed in 2007, eight were deemed suitable based on the following criteria:

- Homeowner cooperation
- Discernible basin shape
- Observable berm definition

After exhausting the 2007 rain garden pool, more recently constructed sites were investigated. Selection was based on number of growing seasons, proximity to the Holmes Lake watershed, and the criteria listed above. Rain garden sizes varied considerably, with areas ranging from 4.8 to 12.7 m^2 (Table 1). This sizing assumes the top of the berm defines the footprint of the rain garden. Candidate homeowners were contacted by phone to explain the project and ask permission to use their rain gardens for the study. For those homeowners who gave permission, a letter was sent to explain the scope of the simulation (Appendix H).

Table 1. General Description of Assessed Rain Gardens.

Rain Garden Site	Footprint Surface Area (m^2)	Construction Date	Roof Runoff Contributing Area (m^2)	Total Catchment Area (m^2)[a]	A_{garden} : $A_{imp\_catch.}$ (%)[b]	A_{garden} : $A_{total\_catch.}$ (%)[c]
1	10.2	2007	49.7	49.7	20.6	20.6
2	9.2	2007	64.9	64.9	14.1	14.1
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	9.35	--	56.1	72.8	19	15
SD	2.33	--	20.3	29.9	8	7

[a] Total catchment area includes roof area plus lawn area, where applicable

[b] Ratio of surface area of the rain garden to the runoff-contributing roof catchment area.

[c] Ratio of surface area of the rain garden to the total catchment (roof + lawn) area.

The roof catchment of each site was delineated by observing where runoff would flow based on downspout location and breaks in the roof. The roof catchment was calculated based on building dimensions measured manually using a tape measure. This area was verified using the GIS program Google Earth (Google Inc., Mountain View, Calif.). Appendix G contains pictures of the twelve rain gardens evaluated.

CHARACTERIZATION OF SOILS

SOIL MOISTURE

Prior to each rain garden evaluation, a JMC Backsaver Handle step soil probe (Clements Associates, Inc.) was used to obtain six soil samples evenly spaced throughout the garden (Figure 6). Each garden was sampled from the top of the soil (i.e. below the mulch layer) to an average depth of 6 cm, which was determined to be a reasonable compromise between adequate sample volume and minimal impact to the garden. Soil samples were collected in order to calculate surface antecedent soil moisture content, to be later correlated with infiltration performance. Each core sample was placed in a tared tin container and sealed with electrical tape and transported to the laboratory within 8 hours. Gravimetric moisture content (dry basis) was measured by placing each core in an oven at 105 °C for 48 h (Dane and Topp, 2002).

Saturation volumetric water content was calculated at each site based on the assumption that this value is equal to porosity. Porosity is 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; Dane and Topp, 2002). Field capacity of each soil sample was calculated assuming the value of field capacity is 60% of porosity (Linn and Doran, 1994).

TEXTURE AND SOIL CLASSIFICATION

Dried moisture content samples from each rain garden were collected into one composite sample and evaluated by Ward Labs (Ward Laboratories, Inc., Kearney, NE) for soil texture and percent organic matter (USDA classification). Because of the high organic matter and amended soils hypothesized to be present in this surface layer, a deeper soil sample was obtained to evaluate the non-amended soil. This was important because, in rain gardens without an under drain, the native soil saturated hydraulic conductivity is often the limiting factor controlling time-of-infiltration and other hydrologic properties (Huwe, 2010). Again a JMC Backsaver Handle step soil probe was used to extract three cores per site with mean depth ranges (±SD) of 6.9 to 39.2 cm (±0.963). These samples were compiled into a composite sample and also sent to Ward Labs for soil texture and organic matter tests.

In addition to soil samples, regional soil maps were analyzed to identify the soil classification of the layer under the rain garden. This was done with the Web Soil Survey website (NRCS, 2011)

Figure 6. Step soil probe (left). Probe extension and soil tins (right).

BULK DENSITY

Sampling for bulk density to convert gravimetric moisture content to volumetric moisture content was done by the core method using a standard sharpened steel cylinder (SSSA, 2002). Three cores were taken from each rain garden using a double-cylinder sampler and a drop hammer to penetrate the soil with minimum vibration (Figure 7). The soil-containing cylinder was removed, and the excess soil was trimmed flush with the steel inner ring (i.d. = 5.45 cm). Dry bulk density was calculated using mass and volume of dry soil.

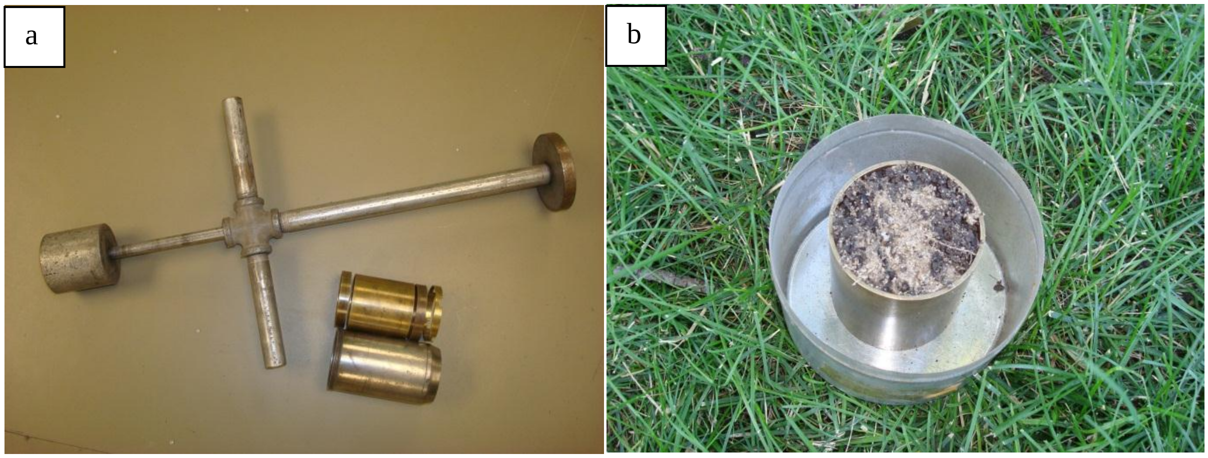


Figure 7. (a) Drop hammer and sharpened steel core with inner sampling ring for bulk density measurement. (b) Shaved soil core using collection equipment. Note the high sand content of the core indicates amendments were added.

Bulk density samples were taken 1-3 days after the simulation or 1-3 days following rain events larger than 0.25 cm (0.1 in.) when rain gardens were assumed to be at field capacity (Linsley and Franzini 1972). Hourly rainfall records used to determine timing of soil sampling were obtained from the High Plains Regional Climate Center, University of

Nebraska-Lincoln from automated weather stations. The weather station used for this study was located 0.44 km (0.27 mi) east of the watershed.

Bulk density values that were obtained during non-ideal, unsaturated conditions were adjusted to bulk density at field capacity for soil types classified as “swelling soils”. This included silty clay loam, clay loam, and clay, and was adjusted based on Sharma’s (1989) adapted equation:

$$\boldsymbol{\rho_{bd,i} = \rho_{bd} - \left[\left(\theta_{g,i} - SL \right) \times \frac{\rho_{bd} - \rho_{bw}}{\theta_g - SL} \right]} \tag{1}$$

where $\rho_{bd,i}$ = dry bulk density at desired moisture content (Mg m^{-3})

ρ_{bd} = dry bulk density sampled (Mg m^{-3})

$\theta_{g,i}$ = gravimetric moisture content desired (%)

θ_g = gravimetric moisture content measured (%)

SL = shrinkage limit (%)

ρ_{bw} = wet bulk density sampled (Mg m^{-3})

The shrinkage limit values used for clay loam, clay, and silty clay soils were 15, 13, and 12% (mass basis), respectively (Sharma, 1989).

HYDROLOGIC MEASUREMENTS

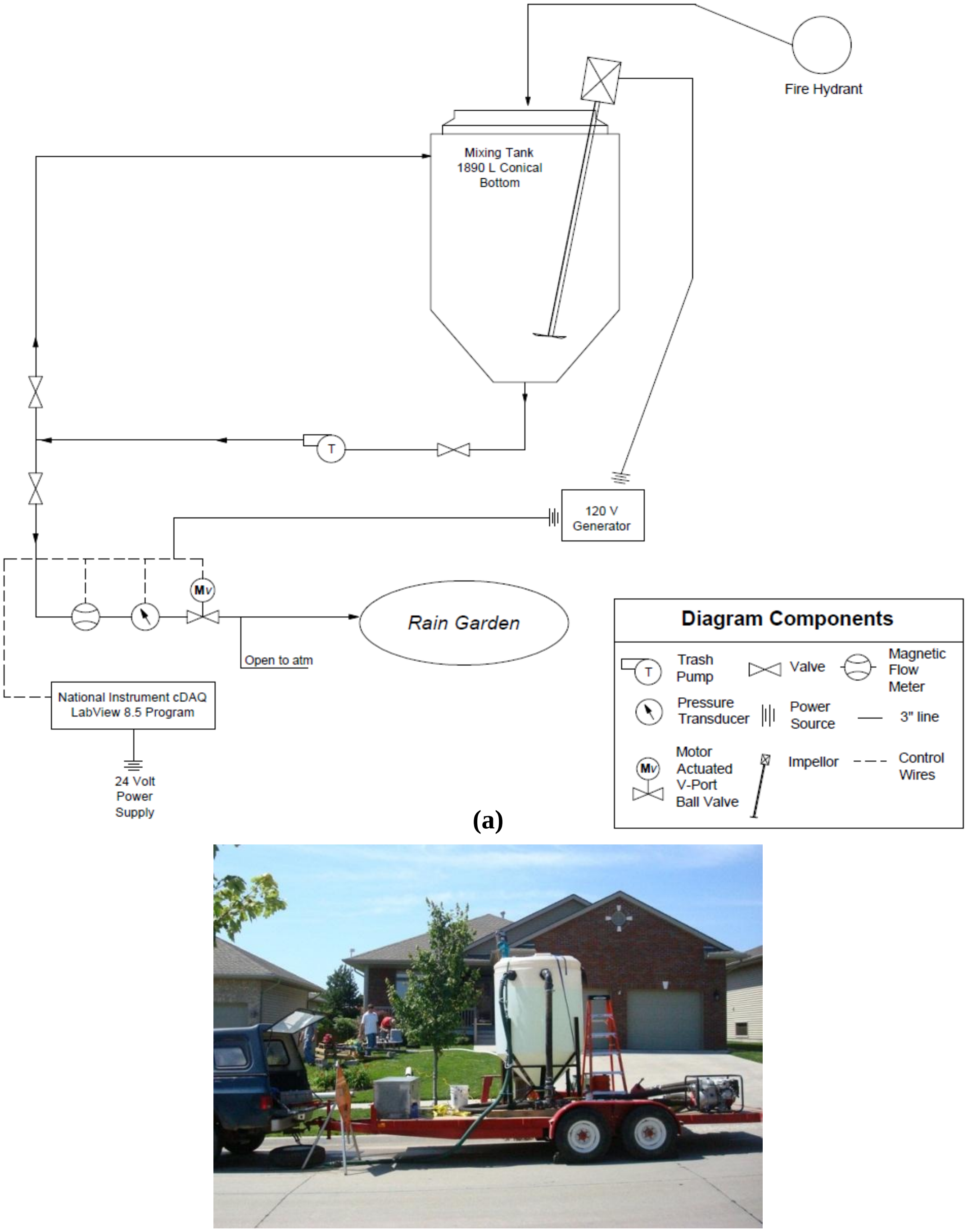
INFLUENT

Stormwater runoff simulation experiments were performed using a modified version of the runoff simulator developed successively by Franti et al. (2007a; 2007b) and Alms et al. (2011). Prior to this study, the simulator system and control program had demonstrated the ability to accurately replicate hydrographs in controlled environments. For this study, the simulator was modified to be mobile for use in residential settings and to operate using fire hydrants as a source for municipal water with permission by the City of Lincoln (Figure 8). Hydrant flow was manually controlled to provide sufficient backup water during all of the simulation runs.

The control system used to regulate the flow from the simulator was designed by Alms et al. (2011). It consisted of a McCrometer full bore magnetic flow meter, an A-T Controls V-port control, a National Instruments Compact Data Acquisition (DAQ) System, and a control program written by Alms in National Instruments LabVIEW^{TM} 8.2.

For each rain garden site, two different storm events were simulated. The first was a volume-based design storm equal to the 90th percentile historical rainfall event for Lincoln, NE. The second event, an overflow event, was designed to have a volume sufficient to over top the rain garden berms. The peak of the overflow event was typically between 1.5 and 2 times the peak of the design storm (Appendix E). The 90th percentile rainfall event, or Water Quality Volume event, has been associated with the removal of 80% of total suspended solids (TSS) on an annual basis (Green Building Council, 2005). Other bioretention design guides also rely on the 90th percentile event (Wisconsin, Iowa State). The storm was determined from a statistical analysis of National Climatic Data Center historical rainfall data

(1948-2010, Lincoln Municipal Airport), excluding events less than 0.25 cm (0.10 in.) (US EPA, 2009). For Lincoln, this storm magnitude is equal to approximately 3.01 cm (1.19 in.) (See Appendix B for procedure)



(a)

(b)

Figure 8. (a) Storm water runoff system schematic. (b) Image of simulator at study site.

This precipitation depth was transformed into runoff using the Natural Resource Conservation Service (NRCS) Curve Number loss method. Because of the low abstraction and atypical watershed characteristics associated with roofs, a modified initial abstraction ratio of $\lambda = 0.05$ was used. Woodward et al. (2004) examined rainfall-runoff data from 307 watersheds across the midwest, east, and south of the U.S., finding that $\lambda = 0.05$ fit observed data much better than the handbook value of 0.20, especially regarding lower precipitation events. Prokop (2003) calculated an initial abstraction ratio of 0.06 in. for storm events discharging into a study bioretention cell, further supporting the use of the lower value for this study. The use of an I_a/S ratio of 0.05 resulted in a altered equations for runoff and curve number (Equation 2 and 3, respectively) from Woodward et al. (2004):

$$Q = \frac{(P - 0.05S_{0.05})^2}{P + 0.95S_{0.05}} \qquad for\ P > 0.5S \tag{2}$$

$$Q = 0 \qquad for\ P < 0.5S \tag{3}$$

Where:

Q = Effective precipitation (cm)
P = Precipitation (cm)
S = Storage given an I_a/S of 0.05 (cm)

$$CN_{0.05} = \frac{100}{1.879\left[\frac{100}{CN_{0.20}} - 1\right]^{1.15} + 1} \tag{4}$$

Where:

$CN_{0.05}$ = Curve number with a I_a/S ratio of 0.05
$CN_{0.20}$ = Curve number with a I_a/S ratio of 0.20

For this study, a curve number of 98 was used for roof areas (Carter and Rasmussen, 2006; USDA-NRCS, 1986) and a curve number of 77 was used for the lawn catchment where applicable. This number represents the average of hydrologic soil groups C and D for "open space (lawn, park)" for good condition grass cover > 75% (USDA-NRCS, 1986).

The runoff volume calculated by the NRCS CN method was transformed into a 30 minute duration hydrograph using the kinematic wave transform method based on applications of this method by Heasom (2006) and others. The modeling was completed using the Hydrologic Engineering Center's Hydrologic Modeling Software (HEC-HMS v. 3.4, Davis, Calif.). Time increments of each hydrograph were adjusted so that the area under the hydrograph curve matched the magnitude of total runoff calculated using the NRCS curve number method. The roof was modeled as one plane, which was assigned an overland flow roughness value of 0.011 for "concrete, asphalt" surfaces (USDA-NRCS, 1986). Roof slope and length were determined by field and aerial measurements in Google Earth. The gutter system delivering water to the rain garden was modeled as a channel feature in the kinematic wave model with an assigned channel roughness of 0.01 based on the University of Warwick's work with domestic roof water harvesting (DTU, 2005). Slope was assumed to be 0.635 cm per 3.05 m (1/4 in. per 10 ft) of gutter (Gutterworks.com). A sample output hydrograph is shown in Figure 9.

Evapotranspiration (ET) was assumed negligible based on the very rapid drainage times discovered in the study. ET was calculated for each site based on the specific day of testing using High Plains Regional Climate Center daily ET data, which was calculated using the FAO Penman-Monteith equation. For each site, ET volume during the event was within 5% of the total volume, which confirmed the negligible ET assumption.

The uncertainty of the measured outflow rate increased below a flow rate of 0.75 L s^{-1}. As a result, the design hydrograph was adjusted to maintain a minimum flow rate of 0.75 L s^{-1} with the same volume as calculated by the NRCS CN method (Table 2). This constraint slightly compressed the raw HEC-HMS hydrographs with respect to time (Figure 9).

Table 2. Water Quality Volume and peak flow for design hydrograph

Rain Garden Site	Runoff Contribution Source (m^2) Roof	Yard	Water Quality Volume (L)	HMS Peak Flow ($m^3\ s^{-1}$)
1	50	0	1569	1.9
2	65	0	1924	2.4
3	37	73	1484	1.4
4	51	67	1852	1.9
5	78	0	2531	2.9
6	79	33	2388	3.0
7	23	0	750	0.9
8	30	9	1062	1.9
9	51	0	1679	1.9
10	70	0	2078	2.6
11	53	20	1762	2.0
12	87	0	2499	3.3

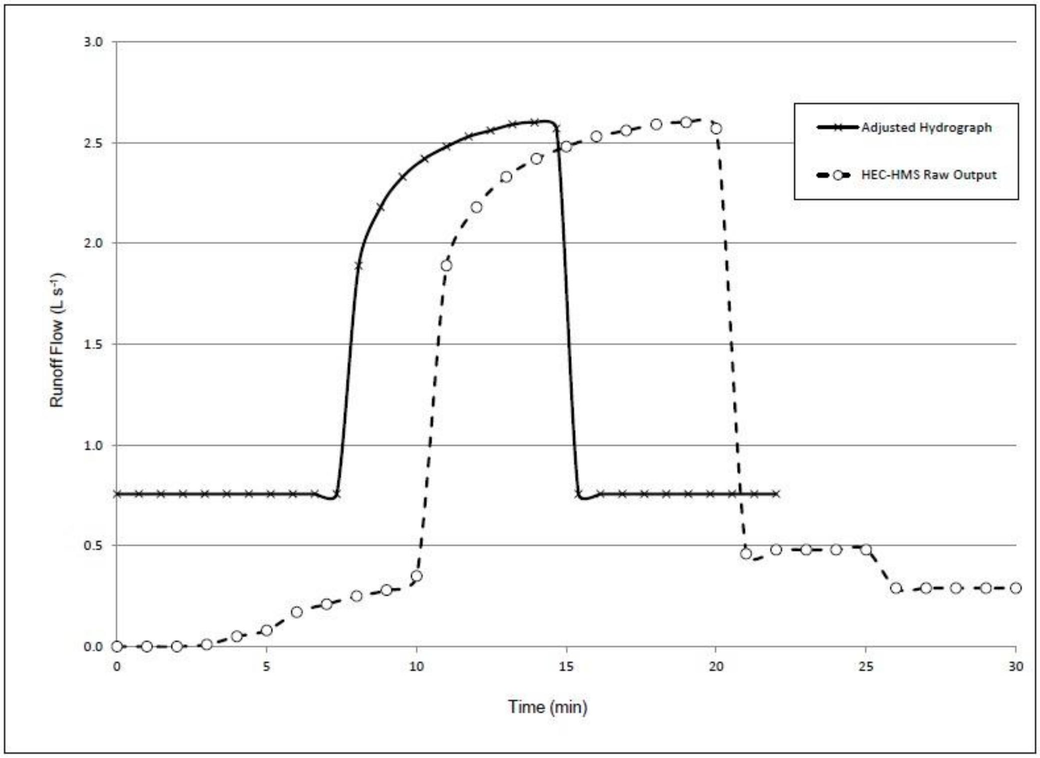


Figure 9. HEC-HMS raw output shown with that same hydrograph adjusted to meet 0.75 L s^{-1} minimum flow requirements. Note same area under each curve maintains same WQV.

Two storm events were simulated per rain garden. For the first storm, the hydrograph described above was applied to the garden until overflow was observed. Once overflow was observed, the simulation was terminated to begin observing drawdown in the rain garden. The purpose of the second simulated storm event was to allow for the evaluation of the overflow structure(s) during a large event, as well as note any other functional weaknesses in the rain garden.

The delivery system (i.e. the valve, meter, and outlet pipe) was set up to introduce water at the designed inlet in each garden. This could be the end of a roof downspout, the location where overland flow from the yard enters the garden, or adjacent to a pop-up riser inlet conveying roof runoff directly into the bed of the garden. The input flow rate for each time step was recorded by the DAQ system receiving input from the valve and the flow meter and automatically transcribed this data into text files by the LabVIEW program. The flow meter was used to calculate volumes applied on each garden. The volume data for site 4 was lost due to human error; therefore, estimation of storm volume holding capacity could not be made.

BASIN MONITORING

Prior to each runoff simulation, the yard drainage area (if applicable) and rain garden basin were defined based upon a survey using a Nikon DTM-520 Total Station. Baseline elevation was recorded in approximate 0.5 m transects across the garden basin with more spatial resolution in areas where topography changes were greater. Elevation was measured at the mulch surface, as this is typically defined as the bottom of the rain garden basin. Elevation was measured outside of the rain garden to define the catchment if it appeared the lawn area contributed overland runoff to the garden. Data was imported and processed in Surfer 10.0 Software (Golden Software Inc, Golden, Colo.), where contour maps could be made to show the lowest point in the garden topographically (Figure 10). Each survey (digitized into a grid by the Kriging method) was analyzed using the Surfer software to obtain an elevation-storage regression relationship to be used in drawdown analysis. Fifteen incremental elevations from the lowest survey point to the highest storage elevation were used to determine volume vs. depth (Table 3).

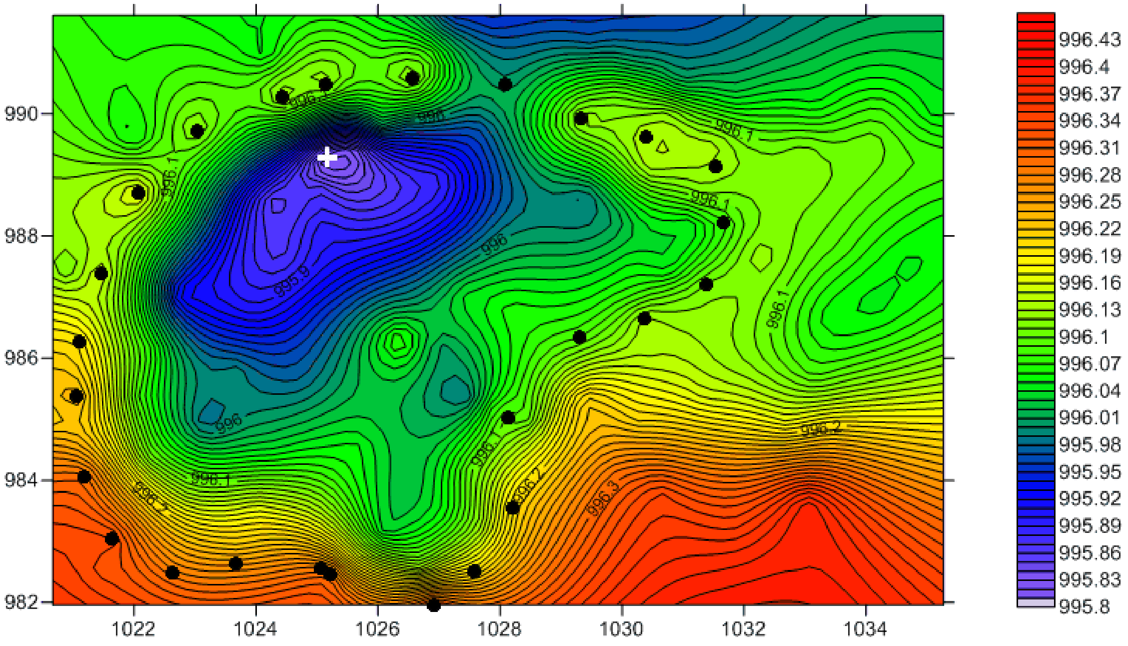


Figure 10. Contour map of rain garden 7. Berm points are illustrated as black circles and the low point is shown as a white cross. Color scale to right is in feet from arbitrary elevation benchmark (Golden Surfer 10.0)

Table 3. Sample of elevation and storage data obtained from survey of site 7 (See Figure 10).

Elevation (m)[a]	Cumulative Depth (m)	Surface Area (m^2)	Storage Volume (L)
303.527	0	0	0.00
303.533	0.006	0.023	0.05
303.539	0.011	0.056	0.27
303.544	0.017	0.156	0.78
303.550	0.022	0.338	2.14
303.555	0.028	0.543	4.59
303.561	0.034	0.739	5.16
303.567	0.039	0.930	12.81
303.572	0.045	1.131	15.55
303.578	0.050	1.356	25.52
303.583	0.056	1.693	34.10
303.589	0.062	1.821	45.00
303.595	0.067	1.821	56.40
303.600	0.073	1.821	67.80
303.606	0.078	1.821	79.20
303.611	0.084	1.821	90.60

[a] Elevation relative to arbitrary survey benchmark.

Other useful information from the survey data included catchment area, rain garden area, and observational data on overland flow drainage patterns into the garden. Additional survey shots were taken at the flagged locations of the highest wetted perimeter of each inundation test (design storm and overflow storm).

For the first event, once any flow left the confines of the rain garden, the simulation was stopped and the water surface perimeter was marked with colored flags (Figure 11). At this point, drawdown starting time was recorded. Drainage time is a performance characteristic important to rain garden and bioretention siting and design. Drainage time was measured for each simulated storm (design storm and overflow) by visually recording the time from maximum ponding to the time ponded water was not visible at the low point.

After water was deemed to be completely infiltrated, the second simulated runoff event was applied to evaluate berm and overflow integrity from a high-discharge inflow. This storm was applied until an approximate steady-state of outflow over the berm was reached, at which point the wetted perimeter was marked with different colored flags. Peak flows for the overflow storm averaged 2.55 L s^{-1}, and typically followed an increasing power function shape.

Water level and drawdown in each rain garden was monitored by using a submersible Solinst Levelogger M5 LT pressure transducer (Solinst Canada Inc., Georgetown, ON, Canada) having a range of 5 m and a precision of 0.005 m. The transducer was installed in a 5.08 cm (2 in.) PVC stilling well. The well was installed at the lowest elevation point determined from survey data to a depth of 13.34 cm (5.25 in.), which placed the lowest hole on the PVC pipe directly at mulch level in the garden. The transducer was suspended from the cap and water was filled up to the first hole, which was a depth of about 0.76 cm (0.3 in.) (Figure 13).

Water level readings were sampled once every 5 seconds to accurately capture any sudden changes in infiltration rate during the drain period. The transducer internal clock was calibrated to the clock used as the reference point for the manual readings. To provide a backup means of drawdown data collection, a staff gage was installed so that the zero-point approximately matched that of the stilling well (Figure 14) and water height recorded manually during each test. To correct any elevation offset due to human error in installation, the ground level zero point of both the stilling well and the gage were surveyed following each simulation.

Basin storage depth was measured in two ways to compare how level the basins were, a key characteristic desired by rain garden designers. Maximum storage depth was measured by the pressure transducer and was defined as the maximum water level before overflow occurred, which is measured at the survey-defined low point in the garden. Additionally, within the wetted surface perimeter of the design storm (WQV), the average basin depth was calculated. This was performed in Golden Surfer 10.0 software by averaging basin elevation values in a 1 ft by 1 ft gridded array for each garden and subtracting those values from the average water elevation reached at the peak of the design storm event.

Figure 11. Garden after second simulated storm showing perimeter flags for each event (differentiated by color).

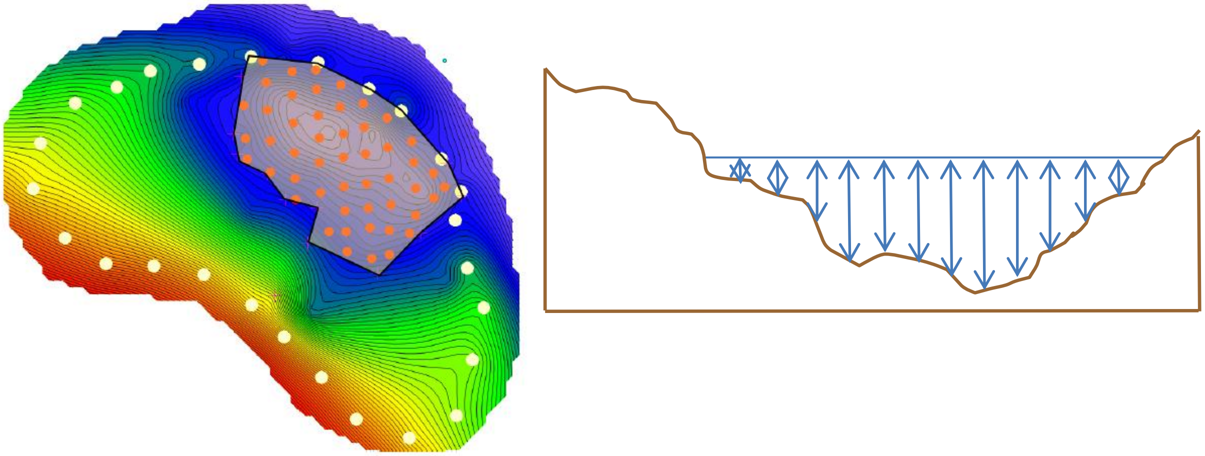


Figure 12. (a) Color contour map of rain garden showing berm definition (white circles), wetted surface area from design storm (shaded polygon), and sample points for depth values (orange circles). (b) Cross-sectional illustration of rain garden showing varying depths sampled. Multiple depths per site resulted in an average value, which can be compared to the maximum to assess how level the basin is.

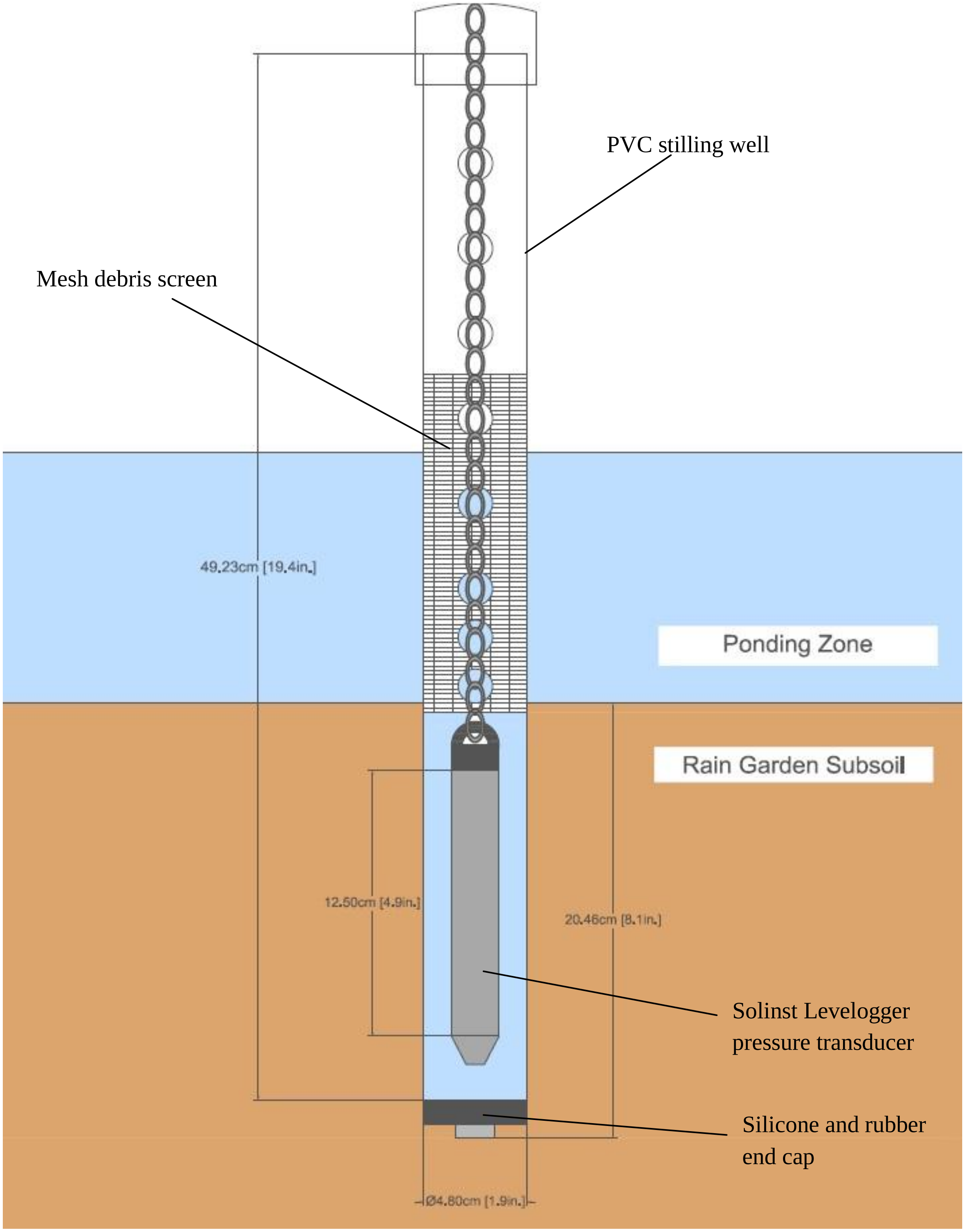


Figure 13.. Cross section of stilling well and transducer in a rain garden with an inundated ponding zone.

Figure 14. Staff gage and stilling well which houses the pressure transducer.

DATA ANALYSIS

The resulting drawdown data from each test resembled the data plotted in Figure 15. The transducer data deviated from the observational staff gage drawdown data by an offset value because the transducer was submerged in a below ground stilling well and as such was adjusted based on this offset. To account for any elevation differences between the well and the staff gage, the water head values were converted to surveyed elevations. The water elevation data from the transducer then was converted to storage volume and surface area via the elevation-storage and the elevation-surface area curves, respectively, developed in Surfer software. Storage and surface area values were then analyzed at 30 second intervals instead of the 5 second sampling rate manually programmed in the transducer. To eliminate noise from the transducer data, both surface area and storage volume were plotted against transducer time and fitted in SigmaPlot with nonlinear regression curves (power and exponential) generally having a coefficient of determination greater than 0.99. For each time step (Δt of 30 s), the change in volume could be computed. Using the Double-End Area Method, the average surface area between two time steps was computed. This value, and the change in volume over the time step, yields an area-averaged infiltration rate as shown below:

$$i_{1-2} = \left[\frac{\Delta V_{1-2}}{\Delta t}\right] \Big/ \left[\frac{(A_1 + A_2)}{2}\right] \tag{5}$$

Where:

i_{1-2} = Infiltration rate, time step 1 to 2 (cm h^{-1})
V_{1-2} = Volume change, time step 1 to 2 (L)
A_1, A_2 = Surface area, time step 1 and 2, respectively (m^2)
Δt = Time interval (30 s)

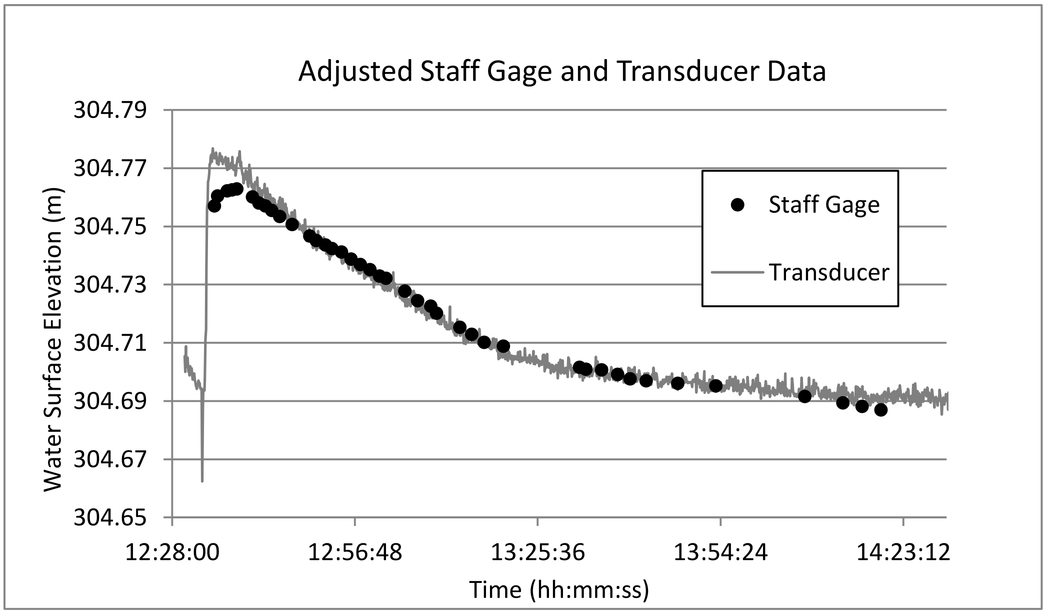


Figure 15. Transducer and staff gage data adjusted to survey-relative elevation.

Infiltration rates curves were produced for both simulated events. Because the second event was larger and resulted in a higher ponding depth, infiltration and draw down time calculations were not started until the ponding water head reached that of the first storm. This allowed for direct comparison of infiltration rate and drawdown time for both storms.

Because infiltration rate typically decreases as soil water content increases (Ward, 2004), one value could not accurately represent an entire drainage 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 manuals.

Statistical analyses were conducted using SAS® version 9.2 (SAS Institute Inc., Cary, N.C.). The level of significance used in all analyses was $\alpha = 0.05$. Linear regression analysis was used to determine the dependence of infiltration and time-to-drain on bulk density, antecedent moisture conditions, organic matter, and soil texture. Pearson coefficients of correlation were calculated for each parameter pair with an assumption of normality. All parameter pairs with correlation (R) magnitudes greater than 0.5 were considered highly correlated. Based on lowest sum of squares, either linear or non-linear regressions were used to fit volume and surface area to elevation and time data.

RESULTS AND DISCUSSIONS

INFLOW

The actual simulated hydrograph input seldom matched the target input. This was because a number of rain gardens were undersized and could not contain the WQV. As a result, there were multiple instances where the simulation had to be stopped during the first storm while the inflow was still at the initial portion of the hydrograph where the flow rate was a constant 0.75 L s^{-1}. A small discrepancy between the flow meter and the target values during this part of the hydrograph results in a distortion of the Nash-Sutcliff Efficiency (NSE) parameter, which works best when comparing a rising, peaking, and falling curve to a theoretical target.

For the second runoff test, a more complete hydrograph curve was simulated, which can better be described by the NSE. The average NSE value (± SD) for the second storm event for all sites was 0.935 (± 0.061), meaning an accurate replication of the input hydrograph was achieved (See Appendix E).

RAIN GARDEN SOIL PROPERTIES

Loam was the most common soil texture found from the analysis of the amended surface layer of the twelve study rain gardens (Table 4). This is in compliance with the Prince George’s County, Maryland Bioretention Manual, which reports that sandy loam, loamy sand, and loam soils are appropriate in bioretention to facilitate the recommended infiltration rate range of 1.27 to 6.1 cm h^{-1}. (Prince George’s County, 2007). However, percent clay values were greater than the 5% recommended by Prince George County. Mean clay content (± SD) of rain garden soils was found to be 23% (± 4.23). The subsoil texture had significantly greater clay content ($p < 0 .0001$) than the surface soil, with a mean of 36% (± 3.32). The sub-soil is typically the limiting layer in rain garden performance (Huwe, 2010).

Organic matter content was fairly consistent among rain garden sites, with a mean value of 8.0 % for surface soil layer (standard deviation of 1.6% when site 11 outlier is excluded). Site 11's rain garden soil had a percent organic content of 25.3 because of homeowner compost replacement a short time before the evaluation. Again the subsoil differed significantly ($p = 0.002$), with a mean organic content of 1.79% (± 0.55). The higher organic matter content in the surface soil layer could be accounted for by compost presence, as well as possible root and soil biotic communities. Increased biological root activity has been linked to increased macropore formation, and thus higher saturated conductivity values in soils (Thompson et al. 2008).

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}). After applying a linear regression statistical analysis, no correlations were found between bulk density and organic matter ($R = -0.072$), bulk density and percent sand ($R = -0.260$), and percent sand and infiltration rate ($R = -0.457$). 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 penetration is likely to be severely restricted. Organic matter is thought to be the major key in reducing bulk density. Organic matter is both a sign of and a factor influencing an active soil biotic ecosystem, which results in the formation of macropores. This can cause lower bulk density values. In addition, organic matter itself has a lower particle density (1.25 g cm^{-3}), which contributes to lower bulk density values.

Table 4. Site Soil Characteristics

Rain Garden Site [a]	Rain Garden Amended Surface Soil (0-6 cm)						Sub-soil Soils (7-39 cm)				
	Sand (%)	Silt (%)	Clay (%)	Texture[b]	OM (%)	Bulk Density (g cm^{-3})	Sand (%)	Silt (%)	Clay (%)	Texture[c]	OM (%)
1	41	38	21	L	7.3	0.95	18	46	36	SCL	2.1
2	42	33	25	L	5.2	0.94	32	32	36	CL	1.4
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	37	40	23		8.0	0.91	22	42	36		1.8
±SD	6.5	5.1	4.2		5.7	0.16	5.7	5.2	3.3		0.6

[a] Color scheme indicates construction year; tan = 2007, blue = 2008, red = 2009

[b] L = loam; SL = silty loam; CL = clay loam; SCL = silty clay loam; SC = silty clay

ANTECEDENT MOISTURE CONDITIONS

June 2011, in which 7 of the 12 evaluations were conducted, was a wetter than normal month for the city of Lincoln. As recorded by a High Plains Regional Climate Center (HPRCC) weather station near the watershed, the precipitation total for the month of June was 16.98 cm (6.69 in.), 54% greater than average. July was a drier month than average, with a 24% decrease from the normal monthly total of 6.9 cm. Regardless of rainfall totals, surface soil antecedent moisture was very high prior to each simulation, commonly resulting in field capacity or higher conditions (Table 5, Figure 16). High soil moisture conditions can also be explained by studies that show soil water content significantly increases with elevated levels of compost and organic matter (Carpenter, 2010). While the dominant soil texture in this study was loam, the presence of high amounts of organic matter results in moisture content values significantly greater than is likely with a more mineral-containing sample. One characteristic noticed in most of the gardens was an extensive mulch layer. This mulch layer may have served two positive functions in the rain gardens: (1) to soak up influent runoff and rain water, thus providing some storage and (2) to help keep the soil moisture capacity higher than would be observed under bare soil conditions (Prince George’s County, 2007). This high soil moisture was observed in every garden.

Table 5. Precipitation and Soil Moisture Data from Rain Gardens, 2011

				Moisture Content			
				Measured Antecedent		Estimated	
Site ID	Date of Simulation	Last rain event prior to simulation (days)[a]	Precip.[b] (cm)	Gravimetric ($g\ g^{-1}$)	Volumetric ($cm^3\ cm^{-3}$)	Saturation[c] ($cm^3\ cm^{-3}$)	Field Capacity[d] ($cm^3\ cm^{-3}$)
1	6/6	6.3	1.40	0.51	0.49	0.63	0.38
2	6/9	0.3	2.03	0.40	0.37	0.64	0.38
3	6/14	5.3	2.03	0.33	0.37	0.57	0.34
4	6/20	2.1	3.25	0.48	0.49	0.66	0.40
5	6/23	1.9	1.88	0.45	0.42	0.63	0.38
6	6/28	1.3	6.32	0.85	0.48	0.78	0.47
7	6/30	3.3	6.32	0.56	0.50	0.65	0.39
8	7/14	6.9	1.24	0.64	0.47	0.71	0.43
9	7/11	3.9	1.24	0.31	0.34	0.58	0.35
10	7/26	18.9	1.24	0.46	0.51	0.57	0.41
11	7/27	0.04	0.33	0.46	0.40	0.60	0.36
12	7/21	13.9	1.24	0.44	0.36	0.70	0.42
			Mean	**0.49**	**0.43**	**0.65**	**0.39**
			SD[e]	0.15	0.06	0.06	0.04

[a] Data obtained with permission from High Plains Regional Climate Center
[b] Rainfall total of last precipitation event prior to simulation
[c] Assumed equivalent to porosity (which assumes organic matter and mineral particle densities of 1.25 and 2.65 g cm^{-3}, respectively; method Avnimelech, et al., 2001).
[d] Calculated: 60% x θ_S (Linn and Doran, 1994).
[e] Standard Deviation

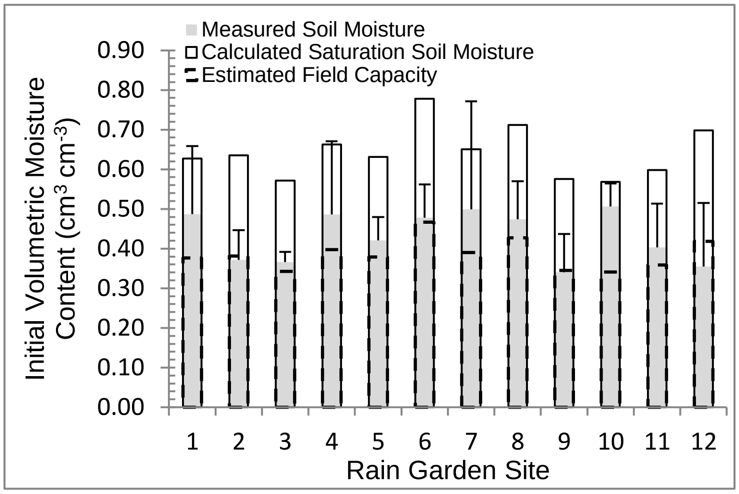


Figure 16. Antecedent moisture prior to each test compared to porosity-based soil saturation and field capacity values. (One-tailed error bars represent standard deviation for antecedent soil moisture).

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 below1 cm h^{-1}, which is below the three selected national bioretention design guidance drainage recommendations (Table 6). A Shapiro-Wilkes test for normality indicated that the log-transformed minimum infiltration rate values follow a normal distribution (W = 0.925, p = 0.398; Normality calculations in Appendix K). 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's Cooperative Extension (Franti and Rodie, 2007). A comparison of infiltration rates to other prominent bioretention design manuals is included in Table 6.

Table 6. Infiltration rate comparison between rain gardens and established design guides during two simulated storms for both fast draining events (gray) and slower events (white).

Site ID	EVENT 1 (DESIGN STORM)				EVENT 2 (OVERFLOW STORM)			
		Bioretention Design Guide[a]				Bioretention Design Guide		
	Minimum Infiltration Rate (cm h^{-1})	NebGuide[b] (0.64 cm h^{-1})	Wisconsin DNR[c] (1.27 cm h^{-1})	PGC[d] (2.54 cm h^{-1})	Minimum Infiltration Rate (cm h^{-1})	NebGuide (0.64 cm h^{-1})	Wisconsin DNR (1.27 cm h^{-1})	PGC (2.54 cm h^{-1})
3	28.0	Y[e]	Y	Y	45.0	Y	Y	Y
9	67.80	Y	Y	Y	18.28	Y	Y	Y
11	70.40	Y	Y	Y	12.7	Y	Y	Y
1	4.13	Y	Y	Y	3.43	Y	Y	Y
2	--	--	--	--	--	--	--	--
4	0.18	N	N	N	0.20	N	N	N
5	4.98	Y	Y	Y	3.91	Y	Y	Y
6	0.38	N	N	N	1.67	Y	Y	N
7	1.37	Y	Y	N	1.03	Y	N	N
8	3.65	Y	Y	Y	0.90	Y	Y	N
10	0.40	N	N	N	0.65	Y	N	N
12	16.20	Y	Y	Y	2.38	Y	Y	N
G.M.[f] Fast	51.1				21.9			
±SD	23.8				17.3			
G.M. Slow	1.61				1.26			
±SD	5.3				1.35			
G.M. All	4.13				2.75			
±SD	26.7				13.5			

[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

Excluding sites 3, 9, and 11, an approaching pseudo-saturated hydraulic conductivity was evident. Sites 3, 9, and 11, drained around an order of magnitude quicker than the rest of the rain gardens, meaning conclusions about long-term drainage and a true minimum infiltration rate value cannot be made with as much confidence. For those rain gardens that drained for a longer period of time and reached lower steady-state values, the geometric mean minimum infiltration rate was 1.61 cm h^{-1} for the design storm. This value exceeds the

NebGuide and Wisconsin DNR rain garden guides, but does not meet the Prince George's County criteria.

Infiltration rate curves were developed for each site and for each event except site 2 (Figure 17). Site 2 had almost no storage capacity, and thus did not have the same drawdown observational treatment applied to it as did the rest of the sites. Because the applied design storm washed out in the same fashion as an overflow storm at the remaining sites, an overflow storm was not applied. The unusual increase in infiltration rate seen on the curve for site 1 is likely due to increased error in the stage-storage and surface-area storage fits as ponding depth approaches zero. The infiltration rates generally follow a decreasing trend, with infiltration rate greatest at the beginning of the drainage period and decreasing with time (Willeke, 1966). Despite the decrease to a lower pseudo steady-state rate, 82% of minimum infiltration rates for all events (22 events) exceeded minimum NebGuide design standards for rain gardens. The variation at the end of the drainage event can be explained by a decreased ability for the surface area-based regression fits to describe physical surface area changes accurately.

Minimum infiltration rate values for each garden for the design storm was strongly negatively correlated with antecedent moisture measured before each run ($R = -0.723$; $p = 0.006$). This relationship has been identified in the literature, as infiltration rates are lower for wet soil than for dry soil (Ward and Trimble, 2004). This is because soil suction decreases with increased water content in the soil, as pores that exert tension forces fill with water. At the beginning of an infiltration event, smaller pores, which exert the greatest tension forces, fill first. Only then do larger pores fill, which rely less on this powerful tension force (Ward and Trimble, 2004).

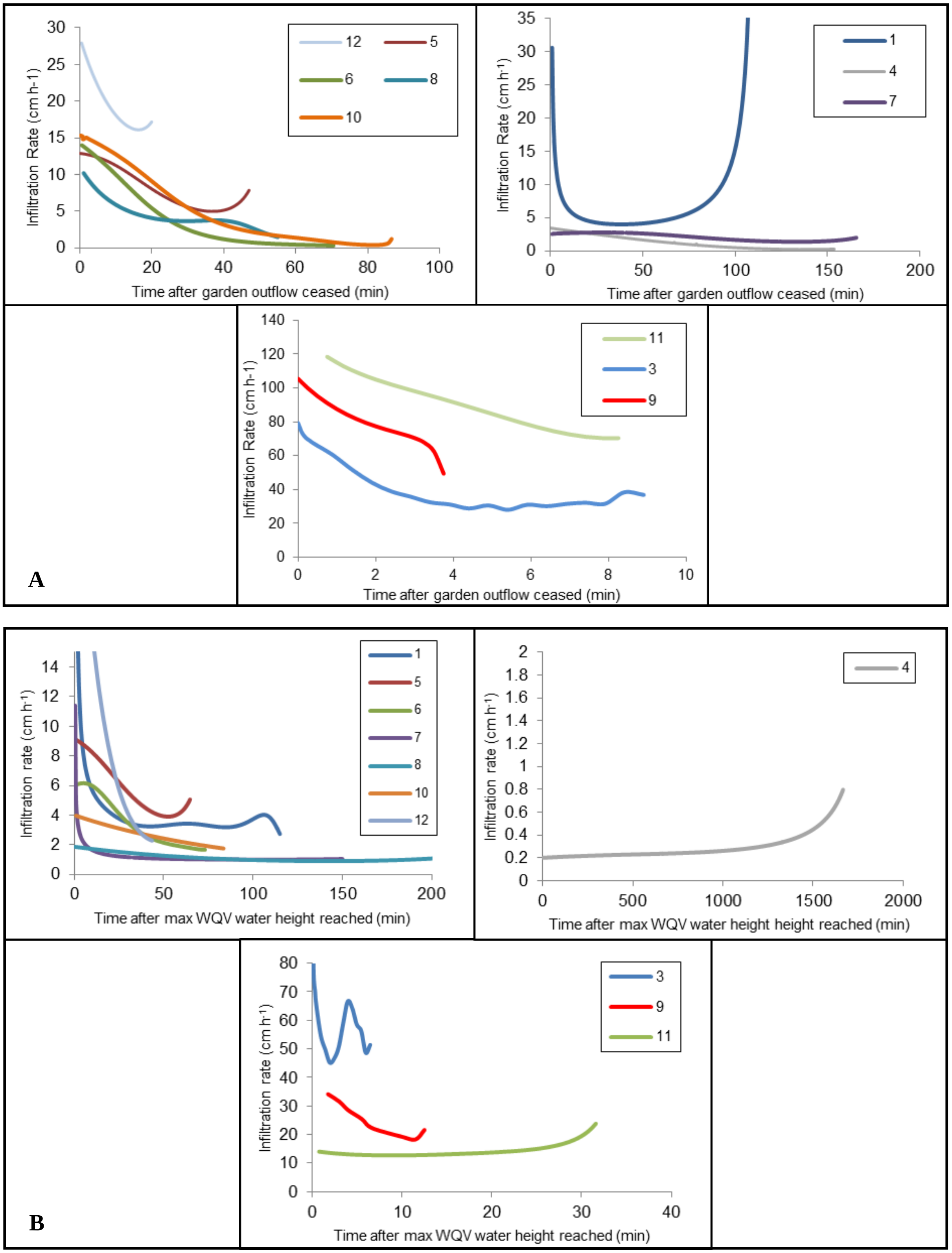


Figure 17. Infiltration rate curves of each rain garden for design storm (A) and overflow storm (B). Three figures per event are used to provide some comparison for gardens with similar time scales. (Site # in legend).

Most of the rain garden surface soils had high initial water content before the simulations took place. Generalizations on specific measured initial soil moisture with regards to infiltration should be made carefully, however, as the moisture content was measured only in the surface of the amended layer. The subsoil initial moisture content is related to infiltration rate as well, but was not measured to minimize disturbance of the rain garden surface.

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.

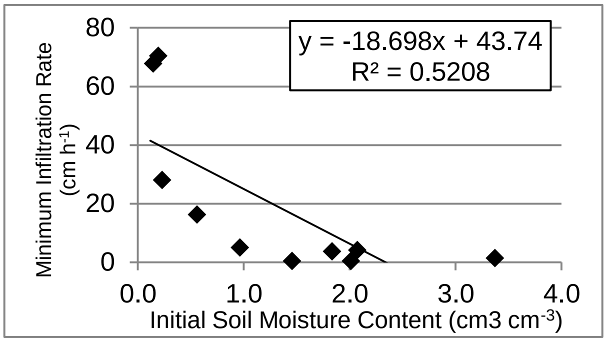


Figure 18. Linear fit of initial soil moisture vs. minimum infiltration rate calculated for the design storm drainage period.

STORAGE CHARACTERISTICS

None of the rain gardens evaluated were able to completely hold the water quality volume storm before overtopping the berm, although sites 1 and 12 were able to accept over 90% of the WQV before overflow occurred (Table 7). The other ten gardens were well below the capacity needed to contain the WQV. On average, there was a wide range of storage capacities observed (Figure 20).

The average ratio of applied volume to the WQV was 40%, with wide variability resulting in a range of 7% to 99% (Table 7). According to design manuals, rain gardens and bioretention cells are designed to not just accept the WQV without overflow, but to actually store this volume above the mulch layer in the ponding zone. This was not found to be the case in any site. The range of the storage capacity-to-WQV values were 3.1% to 23%, indicating that, at the best site studied, only a quarter of the required ponding zone storage was present. Site 6 (pictured in Figure 19 during a natural storm event), is an example of un-utilized rain garden area. Outflow occurs before full storage can be utilized.

By knowing how much water was actually held compared to the water quality volume, enabled back-calculation of the precipitation event the garden actually contained (Table 7). Compared to the WQV precipitation of 3.02 cm (1.19 in.), none of the gardens were able to fully meet the storm storage criteria (Figure 20). Two sites (1 and 11) showed close agreement with the design storm by containing 2.8 and 2.9 cm of precipitation equivalent, respectively, before overtopping. Many gardens, however, far underperformed with respect to this simulated precipitation magnitude. Percentage 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 was lost due to human error during the simulation.

Table 7. Rain garden runoff volume-holding characteristics with respect to the design storm.

Rain garden site	Calculated Design Storm (L)	Water Applied Before Overflow (L)	Surface Storage at Overflow (L)	Volume Infiltrated Before Overflow (L)	Percent of Applied Volume Infiltrated[a]	% Design Storm Volume	Equivalent Precip. Event Capture (cm)[b]
1	1569	1464	306	1158	79%	93%	2.84
2	1924	1463	--	--	--	--	--
3	1484	570	127	443	78%	38%	1.47
4	1852	--	--	--	--	--	--
5	2531	338	151	187	55%	13%	0.60
6	2388	160	75	85	53%	7%	0.41
7	750	158	91	67	43%	21%	0.84
8	1062	382	228	154	40%	36%	1.29
9	1679	591	182	409	69%	35%	1.25
10	2078	323	179	145	45%	16%	0.69
11	1762	1738	393	1344	77%	99%	2.99
12	2499	1034	585	449	44%	41%	1.45
Min.	750	158	75	67	40%	7%	0.41
Max.	2531	1738	585	1344	79%	99%	2.99
Mean	1798	747	232	444	58%	40%	1.47
±SD	546	576	158	451	16%	32%	0.89

[a] Vol. Inf. = volume infiltrated from the start of the simulation to the point of full storage, at which point the simulation was stopped

[b] Back-calculated with curve number equation based on hypothetical capture of full water quality volume storm. Compare to design precipitation magnitude of 3.01 cm

Figure 19. Site 6 rain garden during storm event showing under-utilized basin area. Outflow is occurring over rock overflow structure.

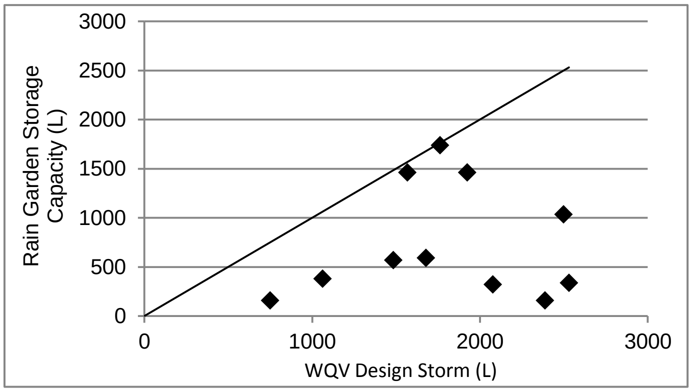


Figure 20. Determined rain garden volume capacity vs design storm volume for each rain garden (blue diamonds). The 1:1 line represents successful capture of WQV.

DEPTH

The average maximum water depth for all sites excluding site 2 was 10.0 cm (3.9 in.) measured from the top of the mulch layer (which is defined as the garden surface). The University of Nebraska Cooperative Extension recommends 3 to 8 in. basin depth measured from, ideally, the uniformly graded berm to the uniform basin surface (Franti and Rodie, 2007). Maximum depths ranged from 7.8 to 12.4 cm (3.1 to 4.9 in.) for the 11 sites. This, however, represents a maximum depth in basins that were observed to be non-uniform. The mean *basin-averaged* depth within the wetted perimeter of all sites' design storms was 4.0 cm (1.6 in.), with a range from 1.8 to 7.7 cm (0.7 to 3.0 in.). The basin-averaged garden depths were significantly lower than the maximum depths ($p<0.0001$). The results of the analysis of average depth calculated for the area inundated for each rain garden's design storm indicates the gardens are shallower than is recommended by Nebraska's rain garden guidelines. Table 8 summarizes the basin storage depth analysis results. Site 3 survey data defining the design storm (WQV) wetted perimeter was lost, resulting in no average storage depth value. Site 1 and 10 had the largest coefficients of variation, which fits with observations of each of those basins' irregular surface topography.

Table 8. Comparison of maximum depths measured at each garden's low spot with basin-averaged depths within the wetted perimeter of the design storm.

Rain Garden Site	Maximum depth (cm)	Average WQV basin storage depth (cm)	Data points considered in basin average[a]
1	10.1	3.4	109
2	--	--	--
3	7.8	--	--
4	12.4	7.7	92
5	10.5	3.5	76
6	8.0	2.9	50
7	8.4	2.8	96
8	7.6	1.8	82
9	11.1	2.8	94
10	11.6	2.4	79
11	11.8	5.6	75
12	11.7	7.1	122
Average	10.0	4.0	88
±SD	1.76	2.0	20

[a] A 1 ft x 1 ft grid was used as the basis for averaging depth data points, which accounts for the varying sample sizes.

DRAINAGE TIME

The mean drainage times (±SD) for the WQV event and the overflow event were 1.61 h (±1.81) and 5.54 (±8.90), respectively, with a maximum time recorded of 30 h. The measured drainage times of the twelve rain gardens are plotted in Figure 21. 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 (EPA 1999; Franti and Rodie, 2007; Wisconson Department of Natural Resources, 2003).

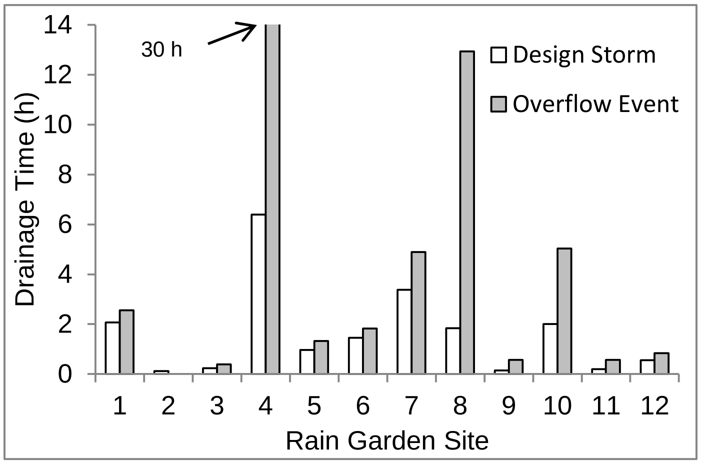


Figure 21. Comparison of measured drain times obtained from two simulated runoff tests. The overflow event for site 4 is 30 h, but was cut off to allow visual comparison of lower drain time values.

OBSERVATIONAL CHARACTERISTICS

VEGETATION COVER

All plants in the rain gardens studied were selected from a standard list of forty-five perennial native and adapted species and cultivars (Liebsch, 2011). The success of these plants depends on many factors including soil moisture, proper grading, mulch cover, time-of-planting, initial maintenance (including weeding and watering), proper sun exposure, amount of compost, and how well plants interact with other species in the garden (Wisconsin Department of Natural Resources, 2003). Some inappropriate plant placement and performance was observed. The rain garden at site 10, which had previously been a standard garden with a rock water feature, had an established tree touching the berm (Figure 22a). In the midwest, trees can disrupt the root growth of native perennial shrubs and grasses. They also restrict sunlight that reaches native plants in the rain garden basin, thus inhibiting growth during the growing season (Franti and Rodie, 2007; University of Wisconson, 2003). Another site had almost no direct sunlight available to the rain garden due to multiple trees in the owner's yard as well as neighboring yards (Figure 22b). Plant growth was severely restricted at this site (Site 3). Four sites excessively large regions of unplanted open space in the rain garden.

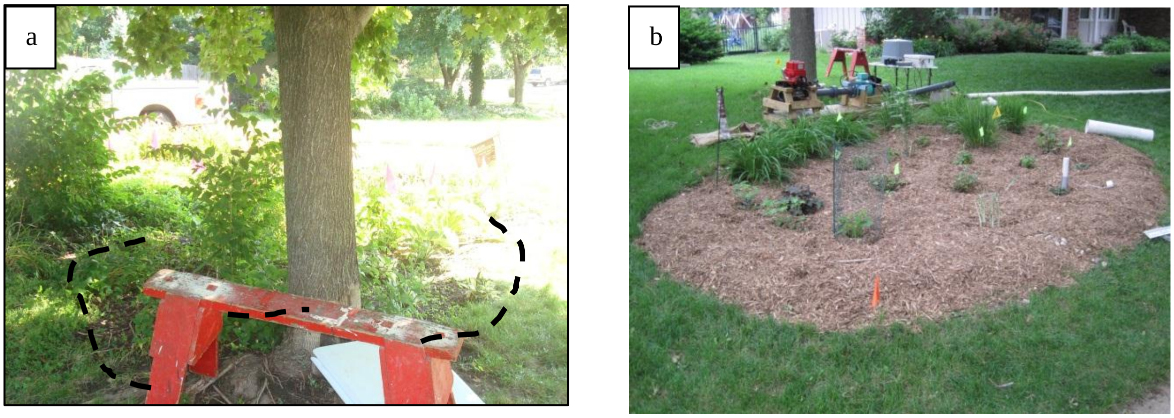


Figure 22. (a) Site with tree near poorly-defined berm (black dashed line). (b) Garden with poor plant density possibly due to under-utilized space and excessive tree shade.

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 23). 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 include:

- Poor grading resulting in the outflow structure not being the lowest elevation of the berm. (Figure 24a)
- Lack of overflow structure (Figure 24b)
- Lack of adequate rock or erosion control at the overflow structure weir (Figure 24c)
- Inadequate width of outflow weir to pass larger flows before widespread overtopping of the berm occurs (Figure 24c)

Figure 23. Photograph of proper site 5 rain garden weir overflow during simulated overflow storm (event 2). Note wet sheen on rock weir where water is flowing.

Figure 24. Photographs of failed overflow structures. (a) Outflow is at a low spot of the berm. (b) Lack of overflow structure. (c) Erosion of berm

Of the ten rain gardens that did have defined outflow structures, four were deemed failing based on one of the following criteria, that (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 24a) resulted in the reconstruction of the berm in that area and reinforcement of the rock overflow structure.

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, much like the situation at site 6 (Figure 25). More care by the designers and installers should result in more retention of volume.

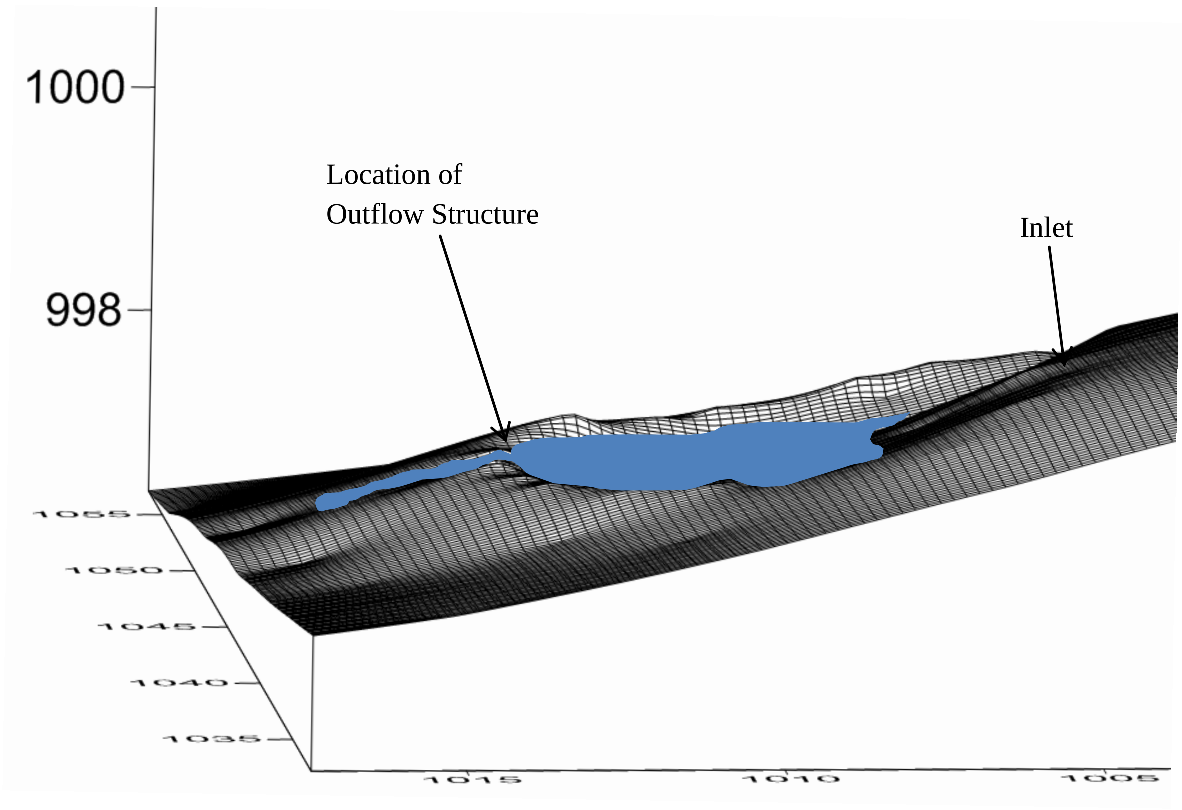


Figure 25. Three-Dimensional wireframe surface of rain garden 6 with water drawn in to show outflow occurs before entire basin can fill. The grading of the upslope half of the rain garden prevents maximum volume capture.

CONCLUSION AND DISCUSSION

Twelve established residential rain gardens were successfully evaluated in the summer of 2011 using a modified version of the runoff simulator developed successively by Franti et al. (2007a; 2007b),and Alms et al. (2011). The following conclusions were drawn from the rain garden study presented:

(1) Effectiveness of rain garden storage capacity was generally poor. None of the rain gardens were able to infiltrate or store the water quality volume design storm of 3.0 cm (1.2 in.) before over topping the berm. The mean percent volume of the design storm able to be successfully captured was 40% for the twelve gardens; however, two sites did perform excellently (1 and 12), managing 93 and 99%, of the water quality storm runoff, respectively. The performance at site 1 is likely caused by a minimum infiltration rate that exceeds design standards (4.13 cm h^{-1}). Site 11 is thought to have captured and held the WQV because of slightly lower initial soil water content (36%) and greater minimum infiltration rate (16.2 cm h^{-1}).

(2) Inability to manage the water quality volume is most likely a result of inadequate basin characteristics rather than a function of soil properties. Berm over-topping was witnessed prematurely in a majority of the gardens studied. The contour maps demonstrate the absence of a level soil/mulch surface at the bottom of most of the gardens. Of the ten gardens demonstrating premature overflow, eight had discrete overflow structures. Of these eight, only three sites possessed overflow structures that functioned as the primary overflow during the course of the simulated overflow event. This indicates that the berm structures meant to contain the water until concentrated overflow can occur are graded improperly, resulting in over topping in multiple unintended locations. Of the sites that demonstrated full functioning of the overflow, an average of only 50% of the garden surface area was inundated at the time of overflow, again indicating improper berm construction or poor grading.

(3) While grading, outflow structure placement, and berm integrity were problematic, soil infiltration rate met the Nebraska rain garden criteria for 73 and 80% of the sites for the design storm and overflow storm, respectively. The geometric mean minimum infiltration rate for the eleven sites was 4.1 cm h^{-1} and 2.8 cm h^{-1} for the design storm and overflow storm, respectively. Design storm event infiltration rates were variable between rain gardens, ranging from 0.18 to 70.4 cm h^{-1}. The three fastest-draining sites (3, 9, and 11) had minimum infiltration rates from 28 to 70 cm h^{-1}. It is hypothesized that the short drain time did not allow the infiltration rate to reach a lower pseudo-steady state value like the other 8 sites. When looking at just the “slower”-infiltrating rain gardens, a general exponentially decreasing trend to a pseudo-steady state infiltration rate value is seen. The average minimum rate among just these sites was 1.6 and 1.2 cm h^{-1} for the design and overflow storms, respectively. While both values exceed the NebGuide minimum, the overflow storm, which was conducted on more saturated soil than the overflow test because it was the second test, demonstrated infiltration rates that generally did not meet the Wisconsin or Prince George’s County guidelines. One must look at the entire event, however, to see that until a pseudo-steady state rate is reached, infiltration rates are higher, yielding a faster drawdown time than would be expected if calculated strictly from the minimum, pseudo-steady state infiltration rate.

(4) The drainage times for all sites were less than the 48-hour maximum inundation period commonly cited by rain garden design manuals to protect against mosquito egg propagation (Franti and Rodie, 2007; EPA, 1999). The average drawdown time (±SD) for the design storm was 1.6 h (1.81 h). Even for the overflow storm, which typically inundated an average of 81% of the rain garden surface area, the average drainage time was 5.54 h (8.9 h), with a maximum measured drain time of 30 h (site 4).

(5) Antecedent soil moisture showed a strong correlation (R = -0.723, p = 0.006) with infiltration rate of the design storm. Antecedent moisture was a good predictor of infiltration rate in this study. Regardless, even the two “wettest” gardens, with initial surface soil moisture contents of 0.50 and 0.499 cm^3 cm^{-3}, had design storm minimum infiltration rates of 4.1 cm h^{-1} and 1.4 cm h^{-1}, respectively, which exceed minimum requirements for standard rain garden guides (Franti et al., 2007; Wisconson DNR, 2003).Understandably, infiltration rate was strongly correlated with drain time (R = -0.722, p = 0.0337).

(6) For those rain gardens not directly connected to roof runoff, improper or inadequate conveyance was observed. For these systems that accept primarily lawn runoff, care should be taken when designing rain gardens to maximize the runoff capture efficiency per square foot. Three of the sites (3, 5, and 11) had unclear catchment areas, and thus may not function properly during an actual storm event. This could result in poor plant performance as well as the inability to capture storm water that instead runs off the property.

(7) Almost every rain garden showed some degree of floating mulch that often washed over the berm, especially during the overflow simulation event. The transport of floating mulch from the basin can have multiple negative consequences, including (1) increased maintenance, (2) increased cost associated with re-mulching, and (3) the export of organic material to the storm water sewer system, which could potentially lead to water quality problems.

The following is a discussion of the ranges of design changes one could make to better store and infiltrate the water quality volume event. For sites that did not contain the design storm (WQV), there are a few key changes that could be made to contain or direct storm water in an adequate way:

- Increase the surface area of the garden to hold the WQV
- Level the garden bottom
- Elevate part or all of the berm to the inlet elevation, keeping the outlet the same
- Elevate the outlet structure, keeping the berm the same

- Elevate the outlet structure, elevate the berm.

Because of the labor and disturbance required for the first two suggestions, it is likely not feasible for these gardens. To see what increase in area would be required to fit the entire WQV in the surface storage zone, the ratio of total storage capacity-to-surface area was calculated. This value was then extrapolated to contain the design storm. This was also done not only for surface storage, but for subsurface storage before the simulation was terminated due to pending outflow (Table 9). The other three suggestions could be attempted in some proportion.

While regarding and excavating 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 (North Carolina Cooperative Extension Service, 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.

Table 9. Estimated increase in surface area needed to capture and infiltrate the Water Quality Volume (WQV) storm.

Rain Garden ID	Area (m^2)	Percent WQV Retained (%)	Additional Surface Area Needed to Hold WQV (m^2)	Surface Area Factor Increase [a]	Comments
6	7.9	7	110.6	14	
5	4.9	13	31.4	6.4	
10	11.7	16	63.3	5.4	
7	5.6	21	20.9	3.7	
9	12.7	35	23.3	1.8	
8	9.0	36	16.0	1.8	
3	10.7	38	17.3	1.6	
12	9.8	41	13.9	1.4	
1	10.2	93	0.8	0.08	Within 10% of WQV
11	11.3	99	0.2	0.02	Within 5% of WQV
2	9.2	76	--	--	Incomplete survey data
4	9.2	--	--	--	Loss of simulator volume data

[a] Area increase assumes (1) same ratio of ponding storage and soil storage as measured in design storm simulation and (2) same media depth.

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Chapter 3 - Summary

Bioretention (e.g. rain gardens) is an important structural best management practice used in low impact development (LID) that has been studied extensively for its positive water quality and volume retention qualities. While the use of rain gardens is increasing due to increased awareness and public acceptance, there is a lack of research detailing how these infiltration devices perform in actual practice.

This research project had three main objectives. They include: (1) comparing established rain garden storage and infiltration capacity to design standards, (2) evaluating the structural integrity of the berm and overflow weir and (3) recommending design changes related to storage ability, garden placement, berm construction and other structural factors. The objectives were accomplished using a modified setup of a runoff simulator system developed by Franti et al. (2007a; 2007b) and Alms et al. (2011). Each of twelve rain gardens evaluated was installed based roughly on available design guides, most notably the NebGuides on rain garden installation and design (Franti et al, 2007). A volume-based design precipitation event of 1.19 inches was applied as downspout runoff on each rain garden in the summer of 2011. Data collected for each rain garden included wetted area of maximum storage (without berm overtopping), antecedent moisture, soil texture, drawdown rate, bathymetric survey, and qualitative observational notes on overall garden performance.

The most important finding from this study was the greater-than-expected infiltration rates and the short drawdown times. The geometric mean of minimum infiltration rate for the overflow simulation event was 2.8 cm h^{-1}, with infiltration rates ranging from 0.65 to 3.4 cm h^{-1} among gardens that performed similarly (all but sites 3, 9, and 11). The NebGuide recommends a minimum infiltration rate of 0.64 cm h^{-1} (0.25 in h^{-1}). This means infiltration rates over 75% of the simulated events met the criteria, for both the design storm and overflow event. The average time-to-drain under wet conditions was found to be 5.54 h with drain times ranging from as short as 0.4 h to as long as 30 h. The Nebguide for rain garden design states that gardens are properly designed if they drain in less than 48 hours (Franti and Rodie, 2007). This criterion was still met for even the most conservative condition on the worst performing garden tested (30 h drain time).

This study also shows that the gardens are undersized with respect to the 3.0 cm (1.19 in.) “Water Quality Volume” (WQV) design storm. The storage capacity of rain gardens can be increased in the future with an increase in ponding depth, increasing surface area or a combination of both. However, these actions mean nothing if the grading of the garden is not done properly. Even an adequately-sized garden on paper may not adequately hold the WQV if, for instance, the outlet weir is at a lower elevation than the upslope berm. If rain gardens are constructed with adequate attention paid to elevation change, then more volume will be captured and infiltrated instead of being passed to the storm sewer system.

While the twelve rain gardens evaluated for this study all had room for improvement, it is not necessarily fair to label any of them as “failing” stormwater best management practices. “Failing” implies a condition no better off than if there wasn’t a rain garden in the first place. Each garden in its own way mitigated a portion of roof or yard runoff, resulting in a net positive gain for the watershed hydrologically. Refinement of design considerations will result in even more successful rain gardens in Lincoln.

FUTURE RESEARCH

Bioretention research is still immature and requires more data to provide quantitative design guidelines for multiple regions, climates, and soil conditions. Aside from the study presented, little research in Nebraska exists on rain gardens. By filling in this knowledge gap, researchers can give decision-makers in the state of Nebraska valuable data which could enable the incorporation of bioretention and LID in city planning. In Nebraska, future studies concerning the effectiveness of rain gardens should include:

- **Continuous monitoring of bioretention/rain garden cells, including inflow and outflow measurements to determine annual volume and peak reduction**. While simulated runoff has been demonstrated as one means to analyze hydrologic characteristics, using meteorological events as runoff sources can provide valuable hydrologic data on roof runoff that can be used to more accurately test these systems in the future.
- **Roof runoff water quality data.** Studies should be done to determine the need for rain garden design to address specific pollutant removal, if necessary, at the residential level. This may aid in more confident TMDL implementation in areas like the Holmes Lake watershed. It would also allow the comparison between the City of Lincoln water used as runoff water with the natural runoff actually seen by the garden.
- **Cost-effectiveness studies for bioretention.** While economic studies exist in certain areas of the U.S. that examine LID cost effectiveness, local studies on the economics and value of rain gardens in Lincoln would aid decision-makers. For

example, when should under drain systems be used? Is it worth the extra engineering cost when soil infiltration capacity may be more than adequate?

- **Further research into water quality effects of organic compost in rain gardens.** Conflicting opinion exists nationally over what the application method of organic carbon in rain gardens should be. Extension specialists in the eastern U.S. maintain that manure-based compost poses a threat to ground water. This may be true considering their unique geology, but what about Nebraska? Future studies should investigate the movement of nutrients in the compost used in rain gardens in Lincoln, and see if those pollutants do pose a threat to ground or surface water.
- **Research on public perception and acceptance of LID over time should be an ongoing pursuit.** Decision-makers on the state and local levels would find much value in up-to-date data from citizens regarding public perception of LID—both structural and non-structural BMPs. While much work has been performed by Meder (2009) in collecting this survey data in the Holmes Lake watershed, persistent outreach could result in improved maintenance (and therefore effectiveness of the practice) and public acceptance of LID.

Along the way, various challenges and surprises were encountered that the author would like the reader to be aware of for future research endeavors. In investigating homeowner rain gardens, it is imperative to investigate the irrigation systems of these homes, as they may be contributing to frequent dry-weather water discharges into the rain gardens. This most definitely occurred at one site during this study.

Future rain garden researchers should perform ring infiltration measurements to confirm or dispute synthetic runoff event infiltration rate values. By measuring antecedent moisture before each type of infiltration test is conducted, the researcher can compare values if applicable. Runoff water sources for infiltration tests should have water quality examinations performed. According to the Food and Agricultural Orgnaication (FAO) (Ayers and Westcot, 1994), rain water has a very low salinity, which may decrease infiltration ability. In addition, rainfall runoff is not as clean as drinking water, as it often contains sediment, which can reduce effective infiltration rate.

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Chapter 4 – Appendix

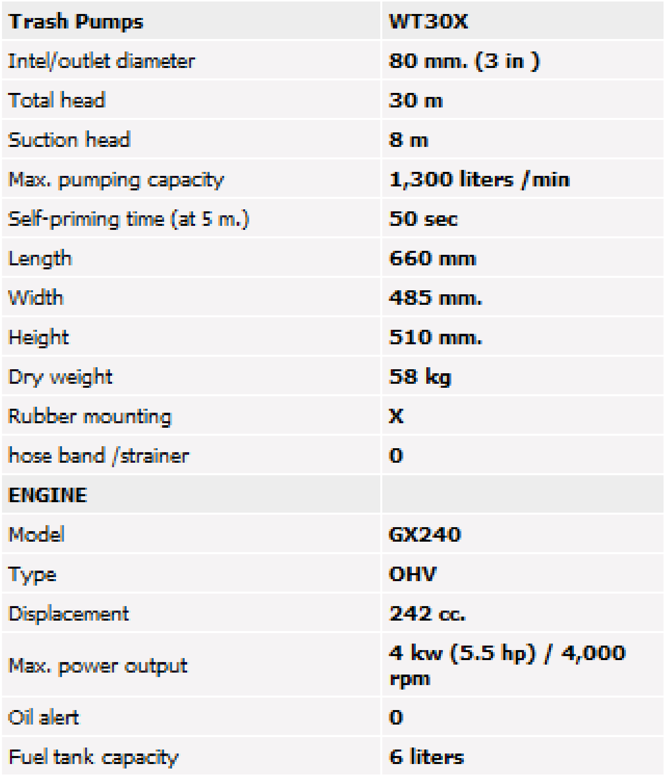
Appendix A: Equipment Specifications

Trash Pump

HONDA
Power
Equipment

Owner's Manual
WATER PUMP
WT20X·WT30X·WT40X

WT30X



Trash Pumps	WT30X
Intel/outlet diameter	80 mm. (3 in)
Total head	30 m
Suction head	8 m
Max. pumping capacity	1,300 liters /min
Self-priming time (at 5 m.)	50 sec
Length	660 mm
Width	485 mm.
Height	510 mm.
Dry weight	58 kg
Rubber mounting	X
hose band /strainer	0
ENGINE	
Model	GX240
Type	OHV
Displacement	242 cc.
Max. power output	4 kw (5.5 hp) / 4,000 rpm
Oil alert	0
Fuel tank capacity	6 liters

Solinst Levelogger (Pressure Transducer):

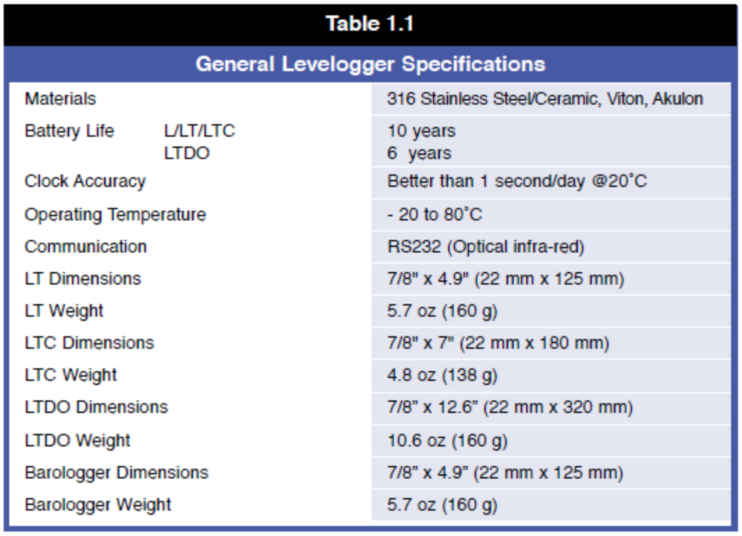


Table 1.1

General Levelogger Specifications

Materials		316 Stainless Steel/Ceramic, Viton, Akulon
Battery Life	L/LT/LTC LTDO	10 years 6 years
Clock Accuracy		Better than 1 second/day @20˚C
Operating Temperature		- 20 to 80˚C
Communication		RS232 (Optical infra-red)
LT Dimensions		7/8" x 4.9" (22 mm x 125 mm)
LT Weight		5.7 oz (160 g)
LTC Dimensions		7/8" x 7" (22 mm x 180 mm)
LTC Weight		4.8 oz (138 g)
LTDO Dimensions		7/8" x 12.6" (22 mm x 320 mm)
LTDO Weight		10.6 oz (160 g)
Barologger Dimensions		7/8" x 4.9" (22 mm x 125 mm)
Barologger Weight		5.7 oz (160 g)

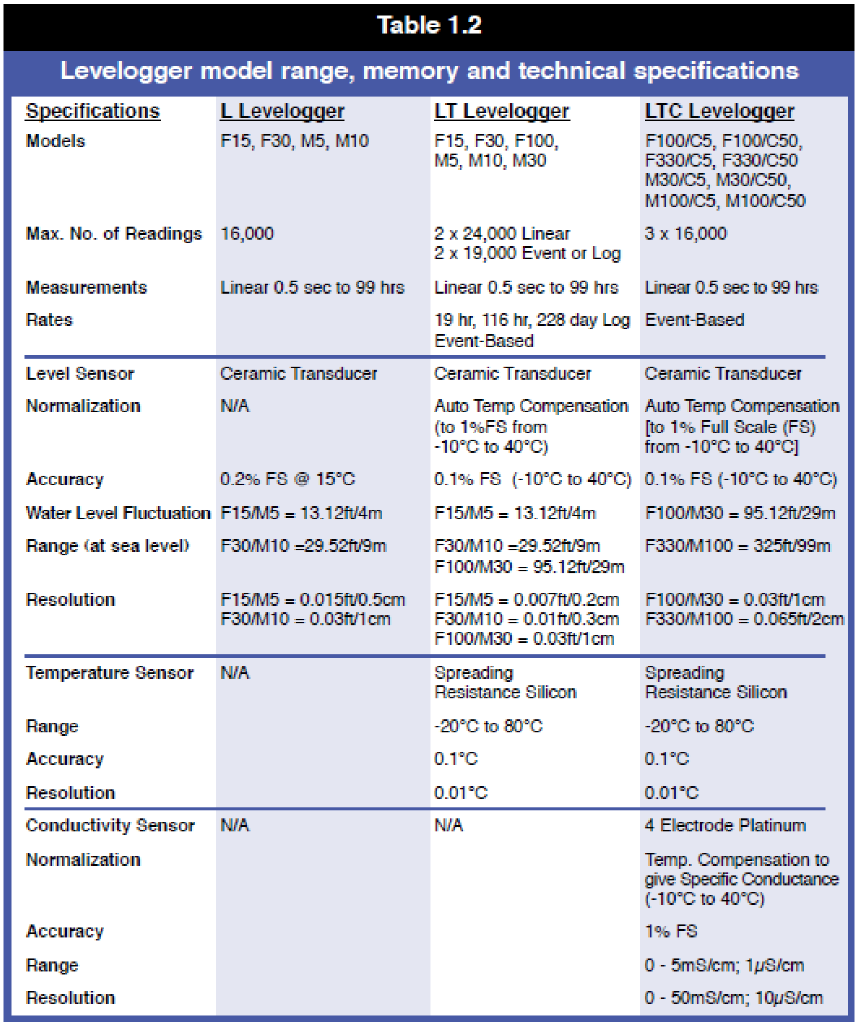


Table 1.2

Levelogger model range, memory and technical specifications

Specifications	L Levelogger	LT Levelogger	LTC Levelogger
Models	F15, F30, M5, M10	F15, F30, F100, M5, M10, M30	F100/C5, F100/C50, F330/C5, F330/C50 M30/C5, M30/C50, M100/C5, M100/C50
Max. No. of Readings	16,000	2 x 24,000 Linear 2 x 19,000 Event or Log	3 x 16,000
Measurements	Linear 0.5 sec to 99 hrs	Linear 0.5 sec to 99 hrs	Linear 0.5 sec to 99 hrs
Rates		19 hr, 116 hr, 228 day Log Event-Based	Event-Based
Level Sensor	Ceramic Transducer	Ceramic Transducer	Ceramic Transducer
Normalization	N/A	Auto Temp Compensation (to 1%FS from -10°C to 40°C)	Auto Temp Compensation [to 1% Full Scale (FS) from -10°C to 40°C]
Accuracy	0.2% FS @ 15°C	0.1% FS (-10°C to 40°C)	0.1% FS (-10°C to 40°C)
Water Level Fluctuation	F15/M5 = 13.12ft/4m	F15/M5 = 13.12ft/4m	F100/M30 = 95.12ft/29m
Range (at sea level)	F30/M10 =29.52ft/9m	F30/M10 =29.52ft/9m F100/M30 = 95.12ft/29m	F330/M100 = 325ft/99m
Resolution	F15/M5 = 0.015ft/0.5cm F30/M10 = 0.03ft/1cm	F15/M5 = 0.007ft/0.2cm F30/M10 = 0.01ft/0.3cm F100/M30 = 0.03ft/1cm	F100/M30 = 0.03ft/1cm F330/M100 = 0.065ft/2cm
Temperature Sensor	N/A	Spreading Resistance Silicon	Spreading Resistance Silicon
Range		-20°C to 80°C	-20°C to 80°C
Accuracy		0.1°C	0.1°C
Resolution		0.01°C	0.01°C
Conductivity Sensor	N/A	N/A	4 Electrode Platinum
Normalization			Temp. Compensation to give Specific Conductance (-10°C to 40°C)
Accuracy			1% FS
Range			0 - 5mS/cm; 1μS/cm
Resolution			0 - 50mS/cm; 10μS/cm

Appendix B: Water Quality Volume Determination Procedure

1. Obtain historical record of daily rainfall of a given location from a climatic database (e.g. High Plains Regional Climate Center or National Climatic Data Center).

2. Exclude storms less than 0.1 inches in magnitude, as these storms are typically too small to cause runoff.[1]

3. Perform statistical analysis of data in Excel. Use the "PERCENTILE" function to find the 90th percentile event. The curve for this study is shown below.

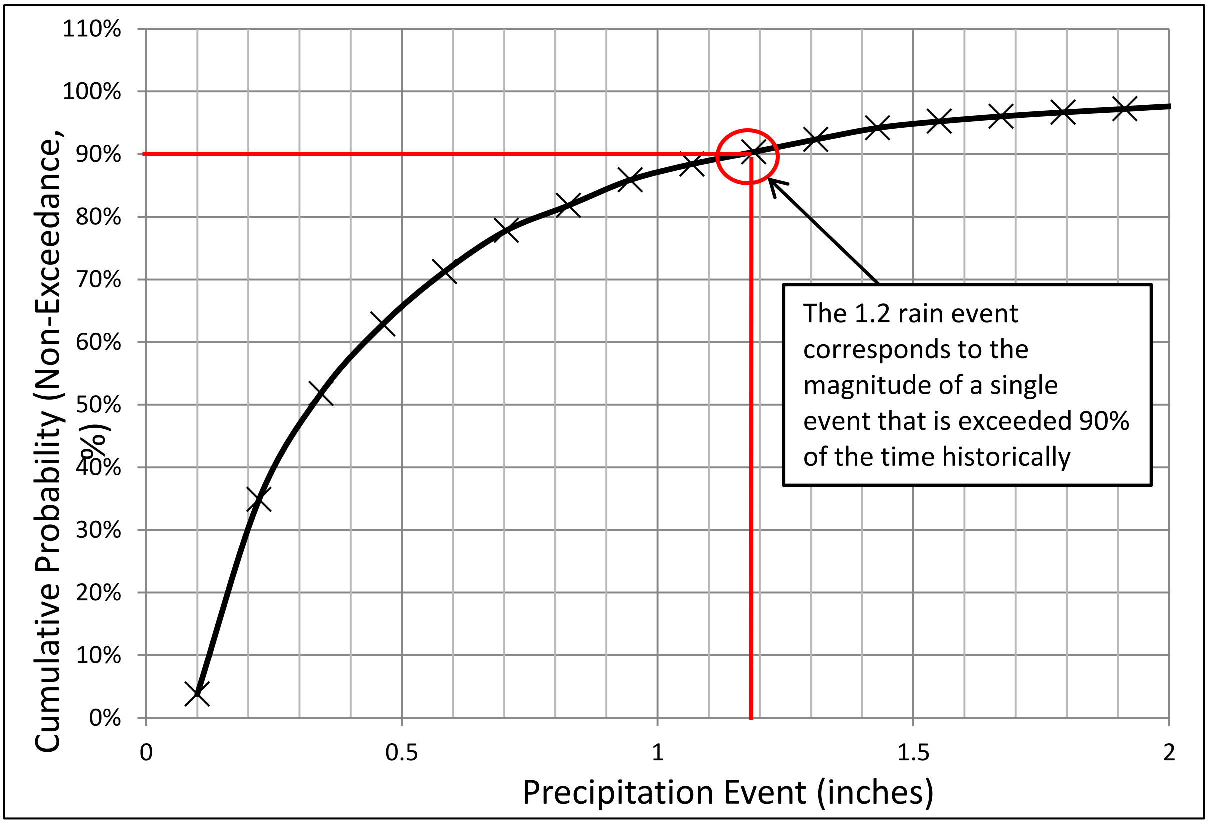


Figure 26.Cumulative probability distribution for 60 years of rainfall data—Lincoln, NE Municipal Airport

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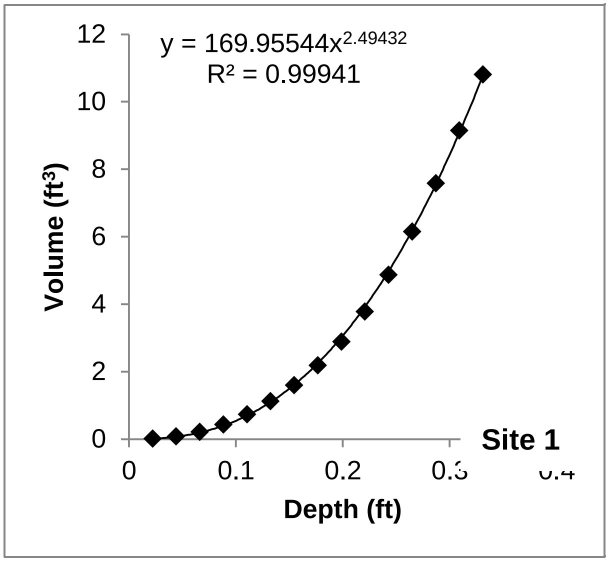
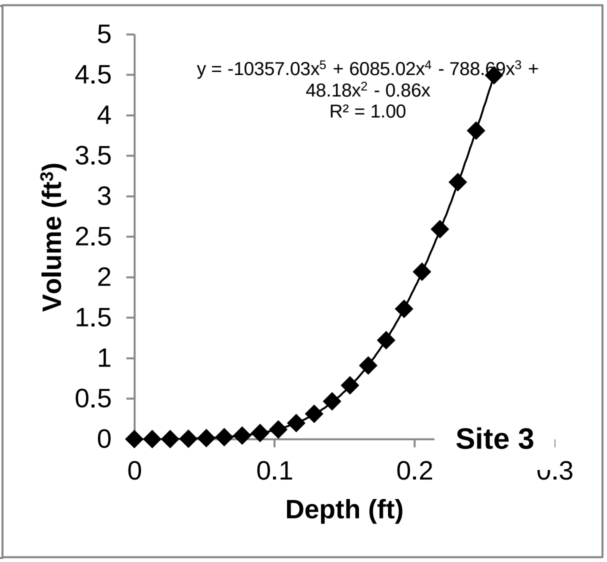
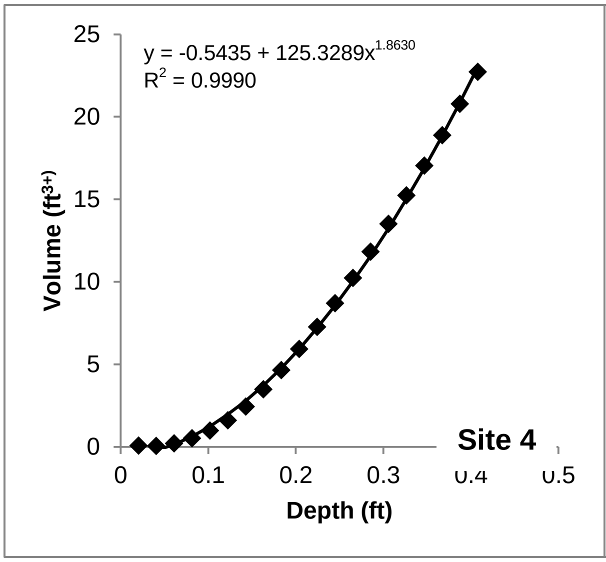
[1] US EPA. 2009. "Technical guidance on implementing the stormwater runoff requirements for federal projects under section 438 of the energy independence and security act"

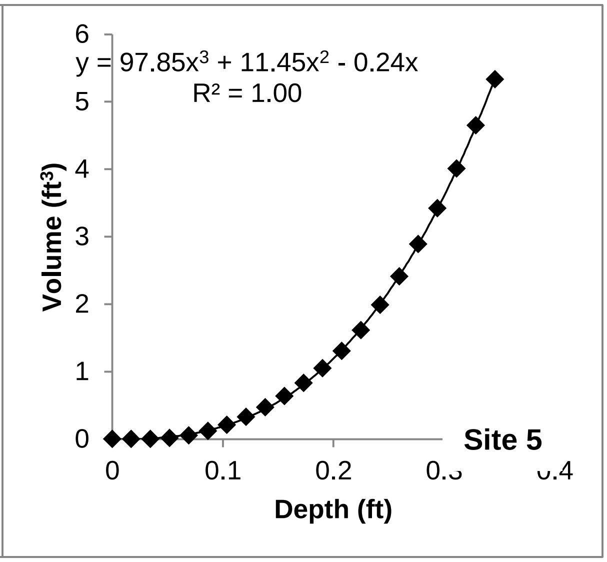
Appendix C: Stage-Storage Curves

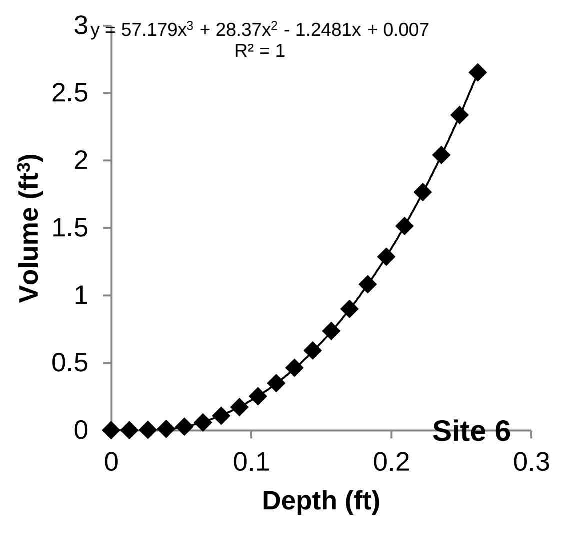
[“y” in all curves denotes storage volume (ft^3), “x” denotes relative water depth (ft)]

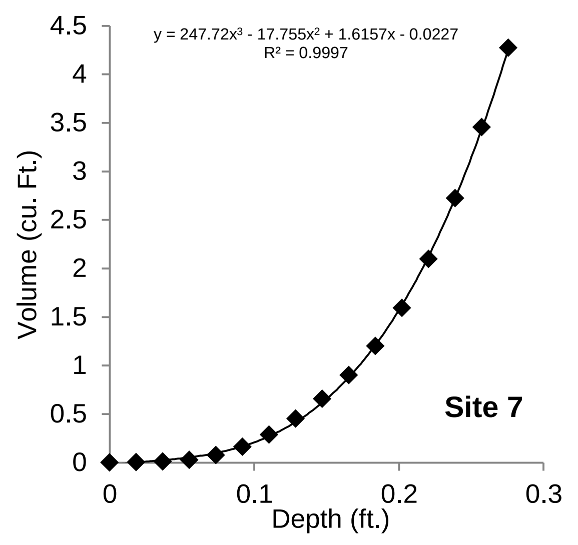


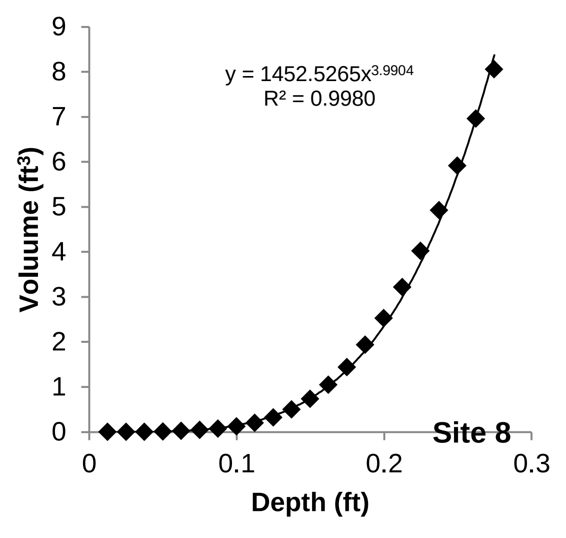


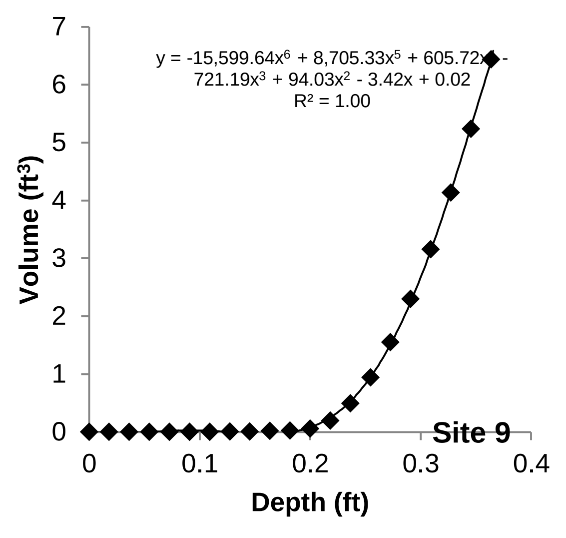


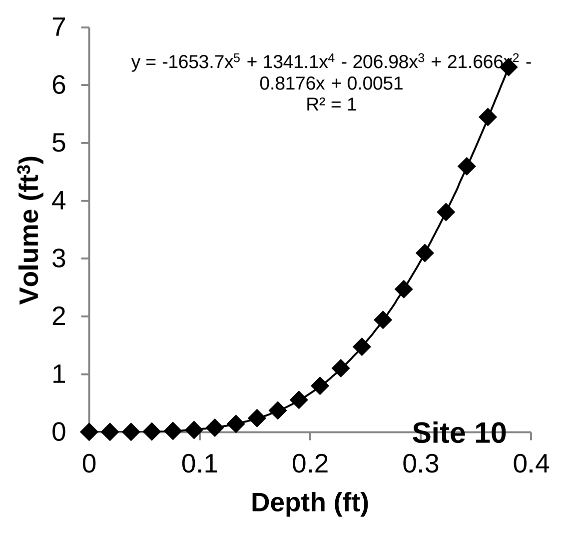


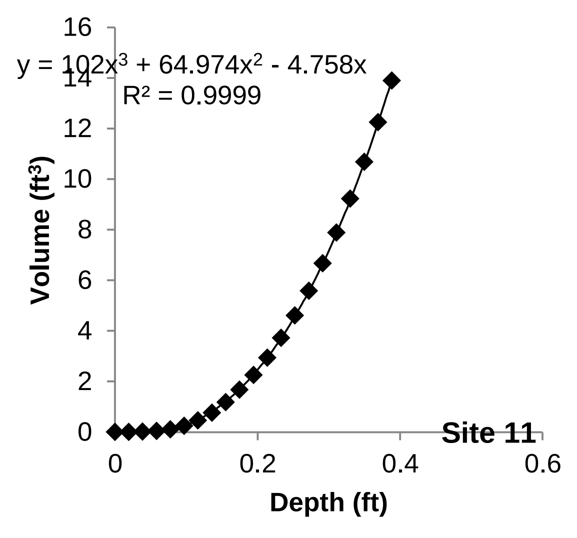

y = 57.179x³ + 28.37x² - 1.2481x + 0.007
R² = 1
Volume (ft³)
0
0.5
1
1.5
2
2.5
3
Depth (ft)
0
0.1
0.2
0.3
Site 6

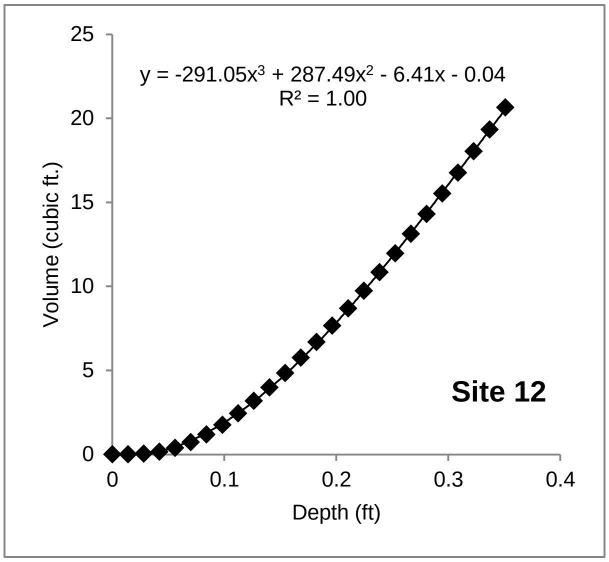

y = 247.72x³ - 17.755x² + 1.6157x - 0.0227
R² = 0.9997
Volume (cu. Ft.)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Depth (ft.)
0
0.1
0.2
0.3
Site 7


y = 1452.5265x^3.9904
R² = 0.9980
Voluume (ft³)
0
1
2
3
4
5
6
7
8
9
Depth (ft)
0
0.1
0.2
0.3
Site 8

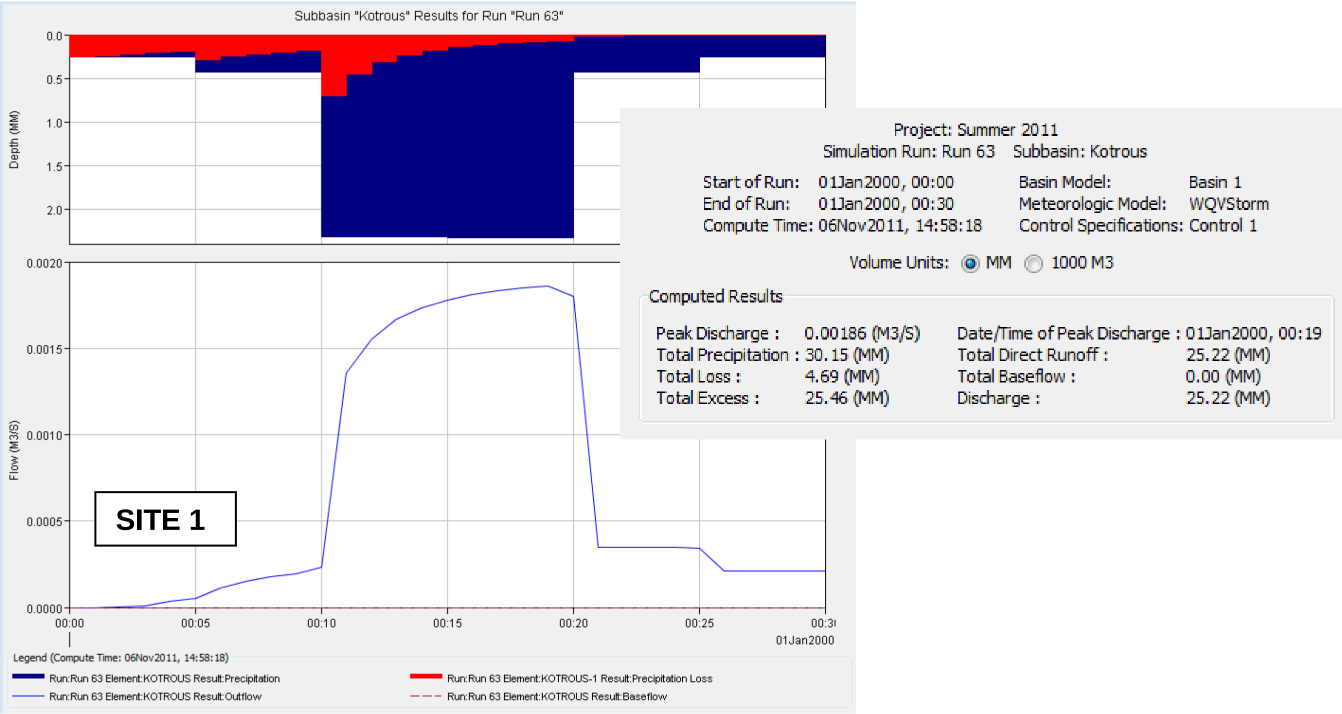

y = -15,599.64x⁶ + 8,705.33x⁵ + 605.72x⁴ - 721.19x³ + 94.03x² - 3.42x + 0.02
R² = 1.00
Volume (ft³)
0
1
2
3
4
5
6
7
Depth (ft)
0
0.1
0.2
0.3
0.4
Site 9


y = -1653.7x⁵ + 1341.1x⁴ - 206.98x³ + 21.666x² - 0.8176x + 0.0051
R² = 1
Volume (ft³)
0
1
2
3
4
5
6
7
Depth (ft)
0
0.1
0.2
0.3
0.4
Site 10


y = 102x³ + 64.974x² - 4.758x
R² = 0.9999
Volume (ft³)
0
2
4
6
8
10
12
14
16
Depth (ft)
0
0.2
0.4
0.6
Site 11


y = -291.05x³ + 287.49x² - 6.41x - 0.04
R² = 1.00
Site 12
Volume (cubic ft.)
Depth (ft)
0
5
10
15
20
25
0
0.1
0.2
0.3
0.4

Appendix D: Input Design Storm Hydrographs (HEC-HMS)



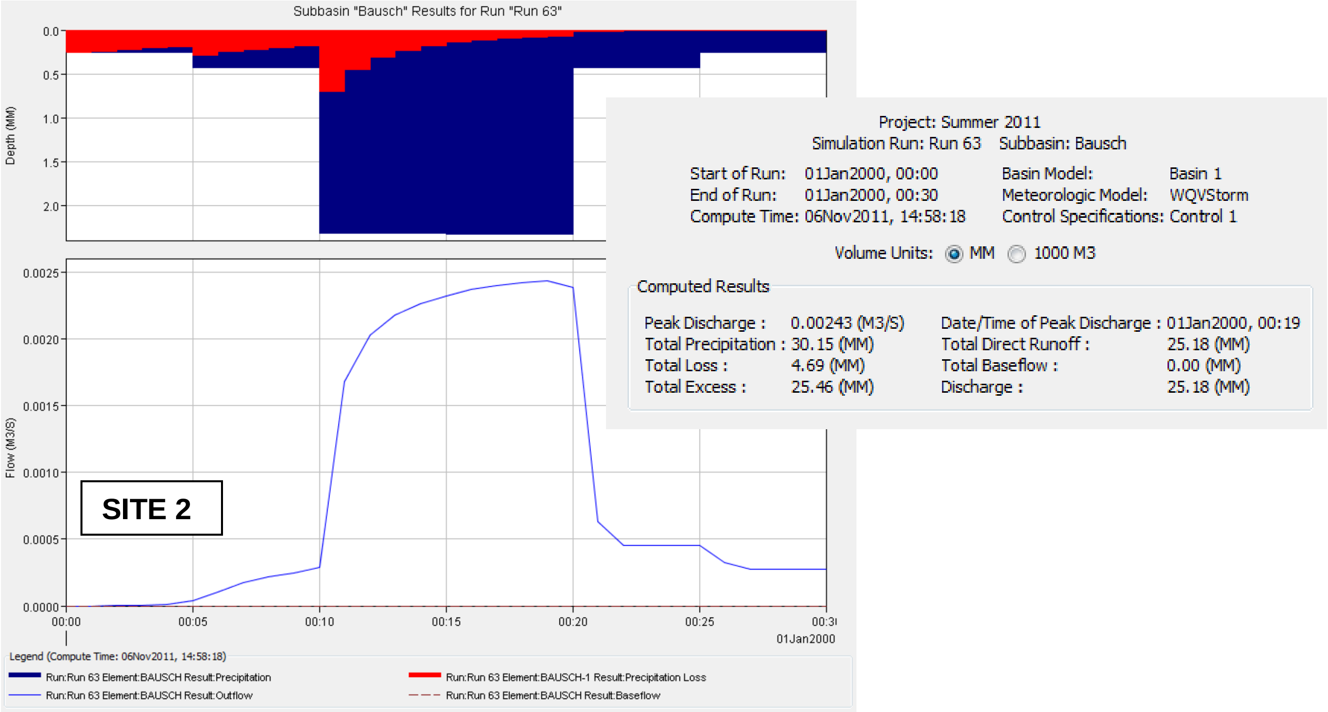
Project: Summer 2011
Simulation Run: Run 63 Subbasin: Kotrous

Start of Run: 01Jan2000, 00:00
End of Run: 01Jan2000, 00:30
Compute Time: 06Nov2011, 14:58:18
Basin Model: Basin 1
Meteorologic Model: WQVStorm
Control Specifications: Control 1

Volume Units: ● MM ○ 1000 M3

Computed Results

Peak Discharge : 0.00186 (M3/S)
Total Precipitation : 30.15 (MM)
Total Loss : 4.69 (MM)
Total Excess : 25.46 (MM)
Date/Time of Peak Discharge : 01Jan2000, 00:19
Total Direct Runoff : 25.22 (MM)
Total Baseflow : 0.00 (MM)
Discharge : 25.22 (MM)



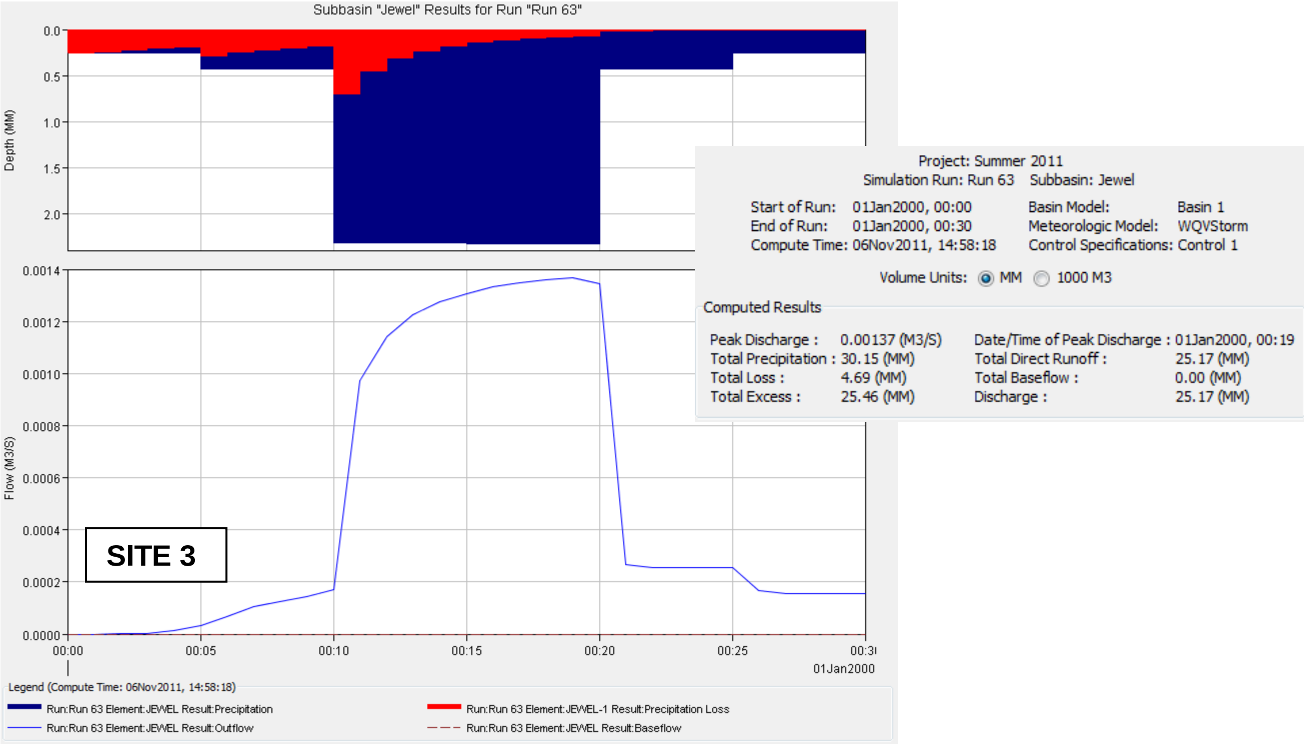
Project: Summer 2011
Simulation Run: Run 63 Subbasin: Bausch

Start of Run: 01Jan2000, 00:00
End of Run: 01Jan2000, 00:30
Compute Time: 06Nov2011, 14:58:18
Basin Model: Basin 1
Meteorologic Model: WQVStorm
Control Specifications: Control 1

Volume Units: ● MM ○ 1000 M3

Computed Results

Peak Discharge : 0.00243 (M3/S)
Total Precipitation : 30.15 (MM)
Total Loss : 4.69 (MM)
Total Excess : 25.46 (MM)
Date/Time of Peak Discharge : 01Jan2000, 00:19
Total Direct Runoff : 25.18 (MM)
Total Baseflow : 0.00 (MM)
Discharge : 25.18 (MM)



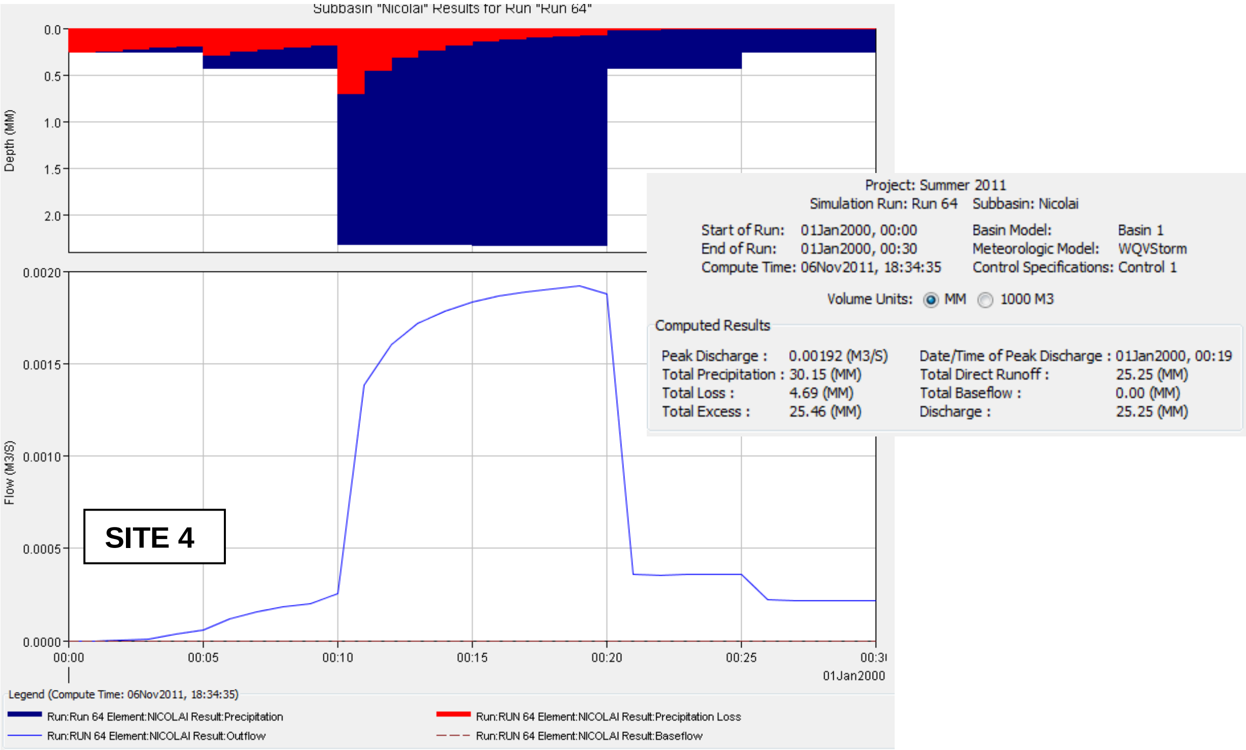
Project: Summer 2011
Simulation Run: Run 63 Subbasin: Jewel

Start of Run:	01Jan2000, 00:00	Basin Model:	Basin 1
End of Run:	01Jan2000, 00:30	Meteorologic Model:	WQVStorm
Compute Time:	06Nov2011, 14:58:18	Control Specifications:	Control 1

Volume Units: ● MM ○ 1000 M3

Computed Results

Peak Discharge :	0.00137 (M3/S)	Date/Time of Peak Discharge :	01Jan2000, 00:19
Total Precipitation :	30.15 (MM)	Total Direct Runoff :	25.17 (MM)
Total Loss :	4.69 (MM)	Total Baseflow :	0.00 (MM)
Total Excess :	25.46 (MM)	Discharge :	25.17 (MM)



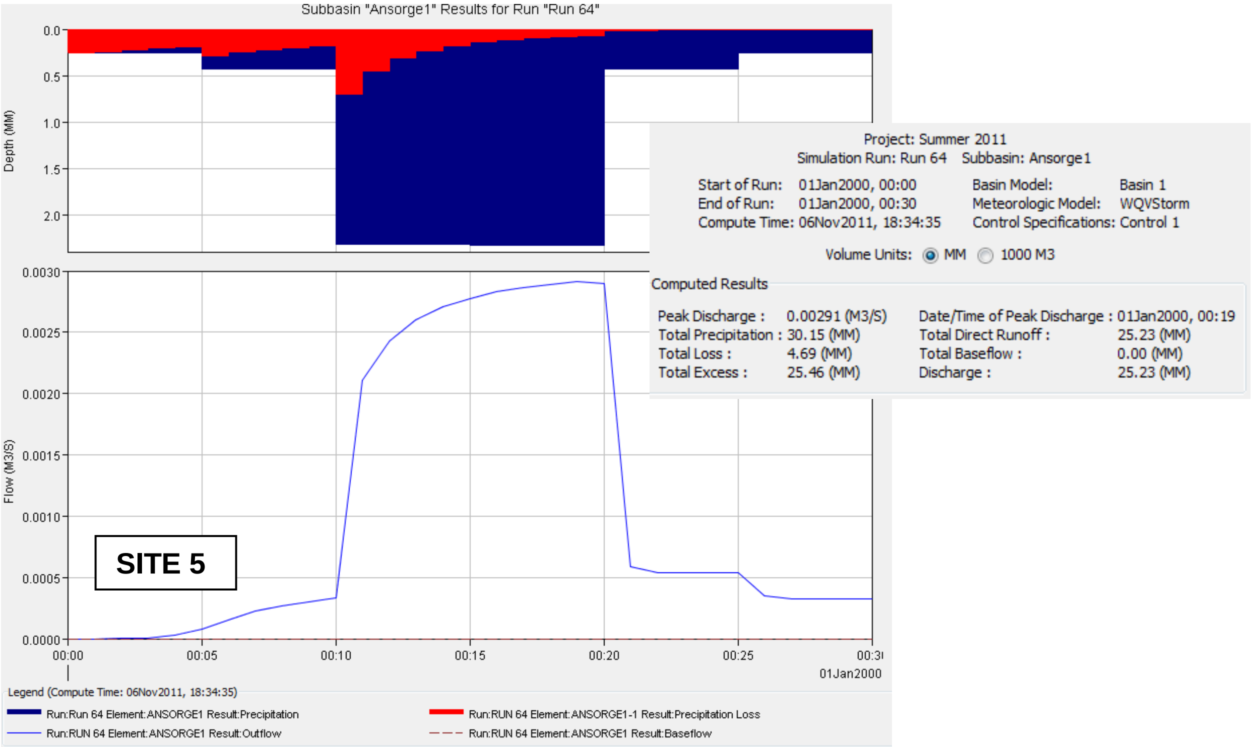
Project: Summer 2011
Simulation Run: Run 64 Subbasin: Nicolai

Start of Run:	01Jan2000, 00:00	Basin Model:	Basin 1
End of Run:	01Jan2000, 00:30	Meteorologic Model:	WQVStorm
Compute Time:	06Nov2011, 18:34:35	Control Specifications:	Control 1

Volume Units: ● MM ○ 1000 M3

Computed Results

Peak Discharge :	0.00192 (M3/S)	Date/Time of Peak Discharge :	01Jan2000, 00:19
Total Precipitation :	30.15 (MM)	Total Direct Runoff :	25.25 (MM)
Total Loss :	4.69 (MM)	Total Baseflow :	0.00 (MM)
Total Excess :	25.46 (MM)	Discharge :	25.25 (MM)



Project: Summer 2011
Simulation Run: Run 64 Subbasin: Ansorge1

Start of Run: 01Jan2000, 00:00
End of Run: 01Jan2000, 00:30
Compute Time: 06Nov2011, 18:34:35

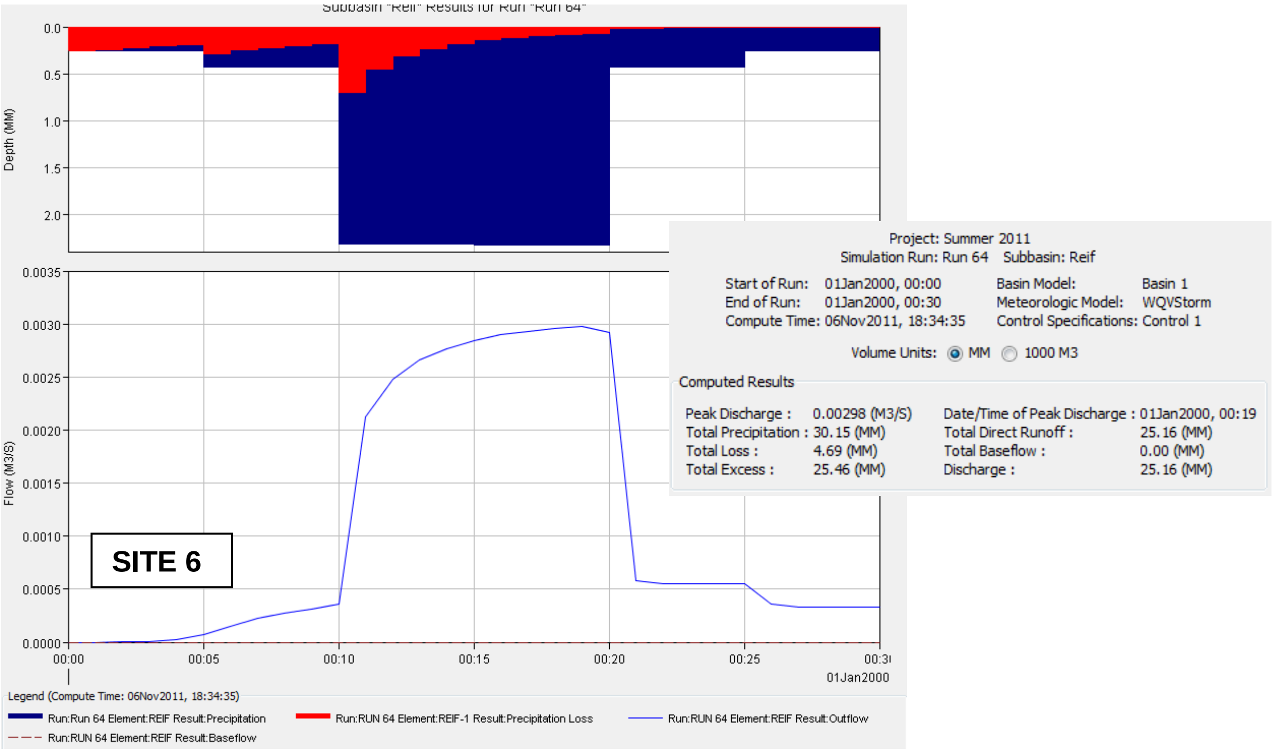
Basin Model: Basin 1
Meteorologic Model: WQVStorm
Control Specifications: Control 1

Volume Units: ● MM ○ 1000 M3

Computed Results

Peak Discharge : 0.00291 (M3/S)
Total Precipitation : 30.15 (MM)
Total Loss : 4.69 (MM)
Total Excess : 25.46 (MM)

Date/Time of Peak Discharge : 01Jan2000, 00:19
Total Direct Runoff : 25.23 (MM)
Total Baseflow : 0.00 (MM)
Discharge : 25.23 (MM)



Project: Summer 2011
Simulation Run: Run 64 Subbasin: Reif

Start of Run: 01Jan2000, 00:00
End of Run: 01Jan2000, 00:30
Compute Time: 06Nov2011, 18:34:35

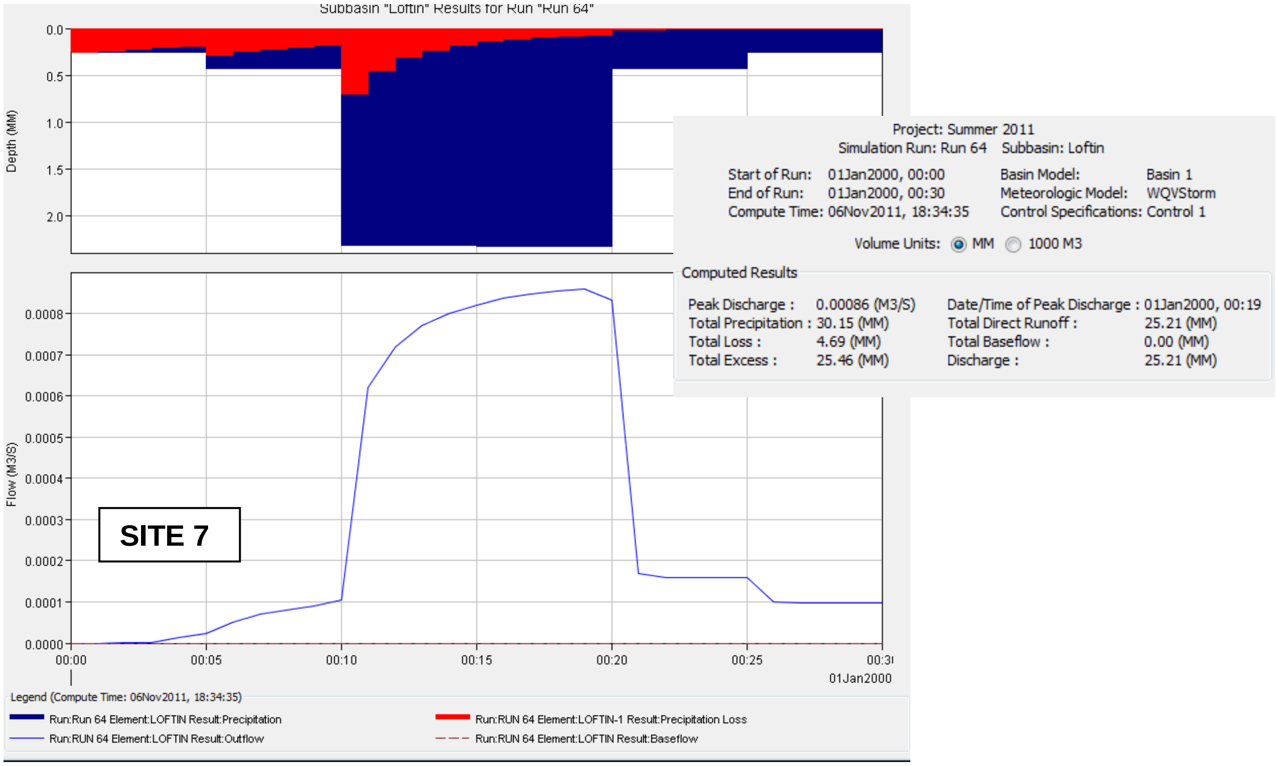
Basin Model: Basin 1
Meteorologic Model: WQVStorm
Control Specifications: Control 1

Volume Units: ● MM ○ 1000 M3

Computed Results

Peak Discharge : 0.00298 (M3/S)
Total Precipitation : 30.15 (MM)
Total Loss : 4.69 (MM)
Total Excess : 25.46 (MM)

Date/Time of Peak Discharge : 01Jan2000, 00:19
Total Direct Runoff : 25.16 (MM)
Total Baseflow : 0.00 (MM)
Discharge : 25.16 (MM)



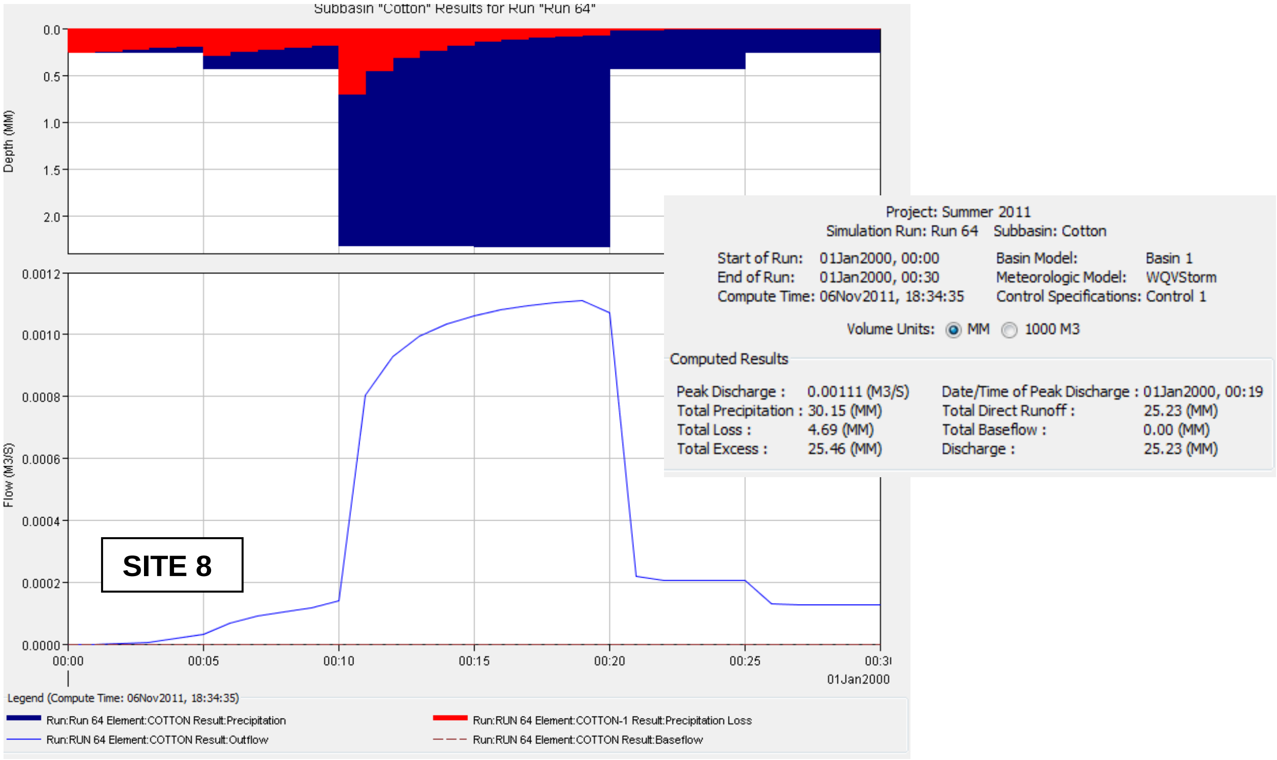
Project: Summer 2011
Simulation Run: Run 64 Subbasin: Loftin

Start of Run: 01Jan2000, 00:00 Basin Model: Basin 1
End of Run: 01Jan2000, 00:30 Meteorologic Model: WQVStorm
Compute Time: 06Nov2011, 18:34:35 Control Specifications: Control 1

Volume Units: ● MM ○ 1000 M3

Computed Results

Peak Discharge :	0.00086 (M3/S)	Date/Time of Peak Discharge :	01Jan2000, 00:19
Total Precipitation :	30.15 (MM)	Total Direct Runoff :	25.21 (MM)
Total Loss :	4.69 (MM)	Total Baseflow :	0.00 (MM)
Total Excess :	25.46 (MM)	Discharge :	25.21 (MM)



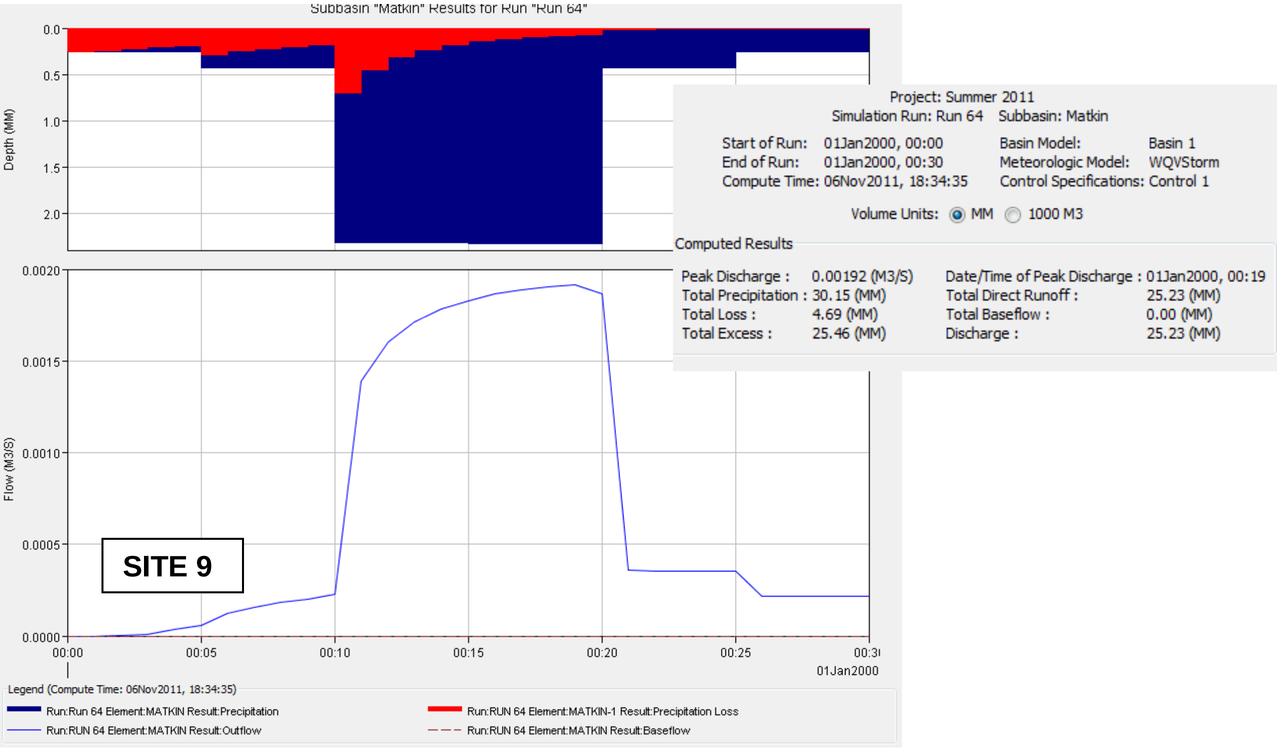
Project: Summer 2011
Simulation Run: Run 64 Subbasin: Cotton

Start of Run: 01Jan2000, 00:00 Basin Model: Basin 1
End of Run: 01Jan2000, 00:30 Meteorologic Model: WQVStorm
Compute Time: 06Nov2011, 18:34:35 Control Specifications: Control 1

Volume Units: ● MM ○ 1000 M3

Computed Results

Peak Discharge :	0.00111 (M3/S)	Date/Time of Peak Discharge :	01Jan2000, 00:19
Total Precipitation :	30.15 (MM)	Total Direct Runoff :	25.23 (MM)
Total Loss :	4.69 (MM)	Total Baseflow :	0.00 (MM)
Total Excess :	25.46 (MM)	Discharge :	25.23 (MM)



SITE 9

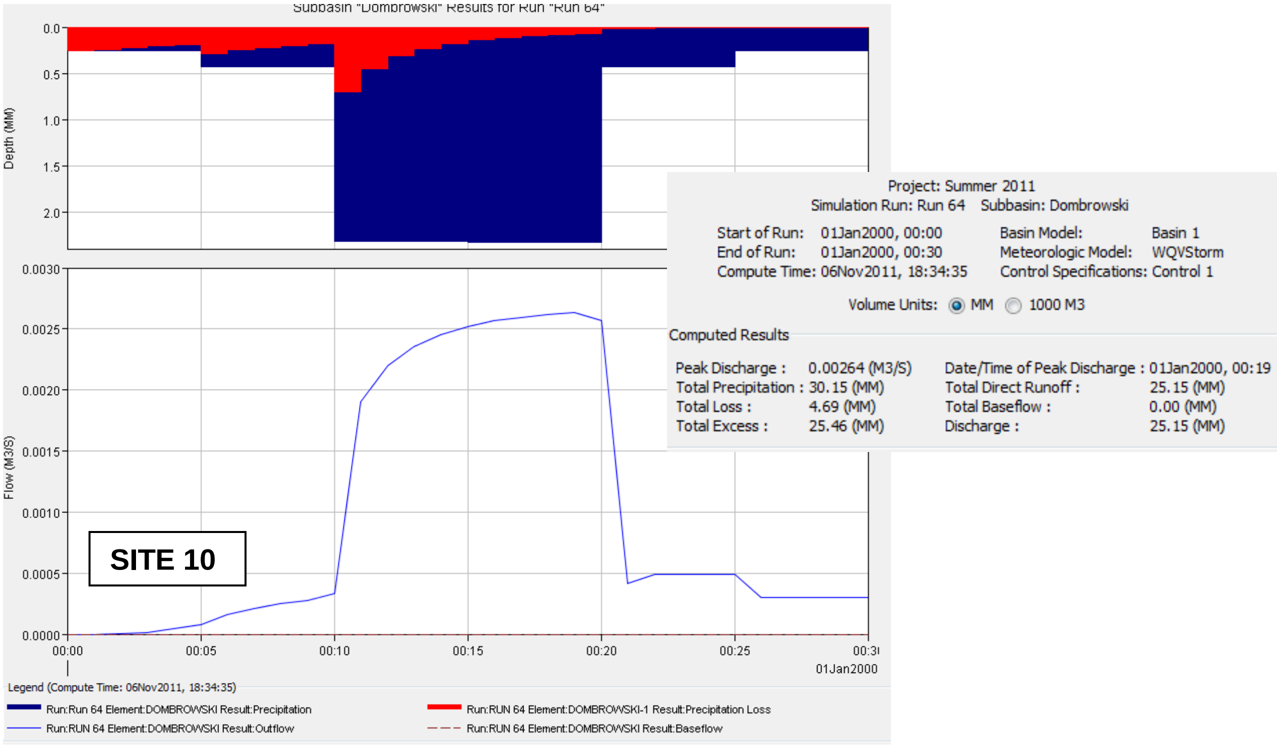
Project: Summer 2011
Simulation Run: Run 64 Subbasin: Matkin

Start of Run: 01Jan2000, 00:00 Basin Model: Basin 1
End of Run: 01Jan2000, 00:30 Meteorologic Model: WQVStorm
Compute Time: 06Nov2011, 18:34:35 Control Specifications: Control 1

Volume Units: ● MM ○ 1000 M3

Computed Results

Peak Discharge : 0.00192 (M3/S) Date/Time of Peak Discharge : 01Jan2000, 00:19
Total Precipitation : 30.15 (MM) Total Direct Runoff : 25.23 (MM)
Total Loss : 4.69 (MM) Total Baseflow : 0.00 (MM)
Total Excess : 25.46 (MM) Discharge : 25.23 (MM)



SITE 10

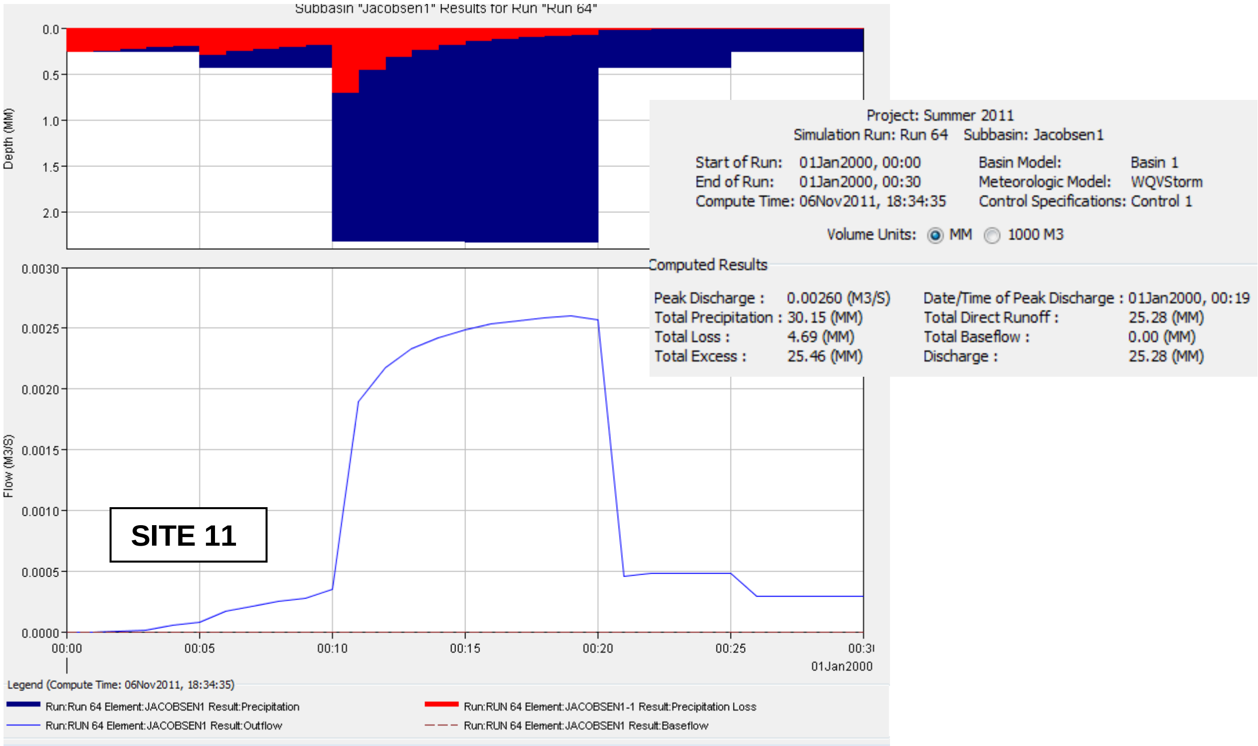
Project: Summer 2011
Simulation Run: Run 64 Subbasin: Dombrowski

Start of Run: 01Jan2000, 00:00 Basin Model: Basin 1
End of Run: 01Jan2000, 00:30 Meteorologic Model: WQVStorm
Compute Time: 06Nov2011, 18:34:35 Control Specifications: Control 1

Volume Units: ● MM ○ 1000 M3

Computed Results

Peak Discharge : 0.00264 (M3/S) Date/Time of Peak Discharge : 01Jan2000, 00:19
Total Precipitation : 30.15 (MM) Total Direct Runoff : 25.15 (MM)
Total Loss : 4.69 (MM) Total Baseflow : 0.00 (MM)
Total Excess : 25.46 (MM) Discharge : 25.15 (MM)



Project: Summer 2011
Simulation Run: Run 64 Subbasin: Jacobsen1

Start of Run: 01Jan2000, 00:00
End of Run: 01Jan2000, 00:30
Compute Time: 06Nov2011, 18:34:35

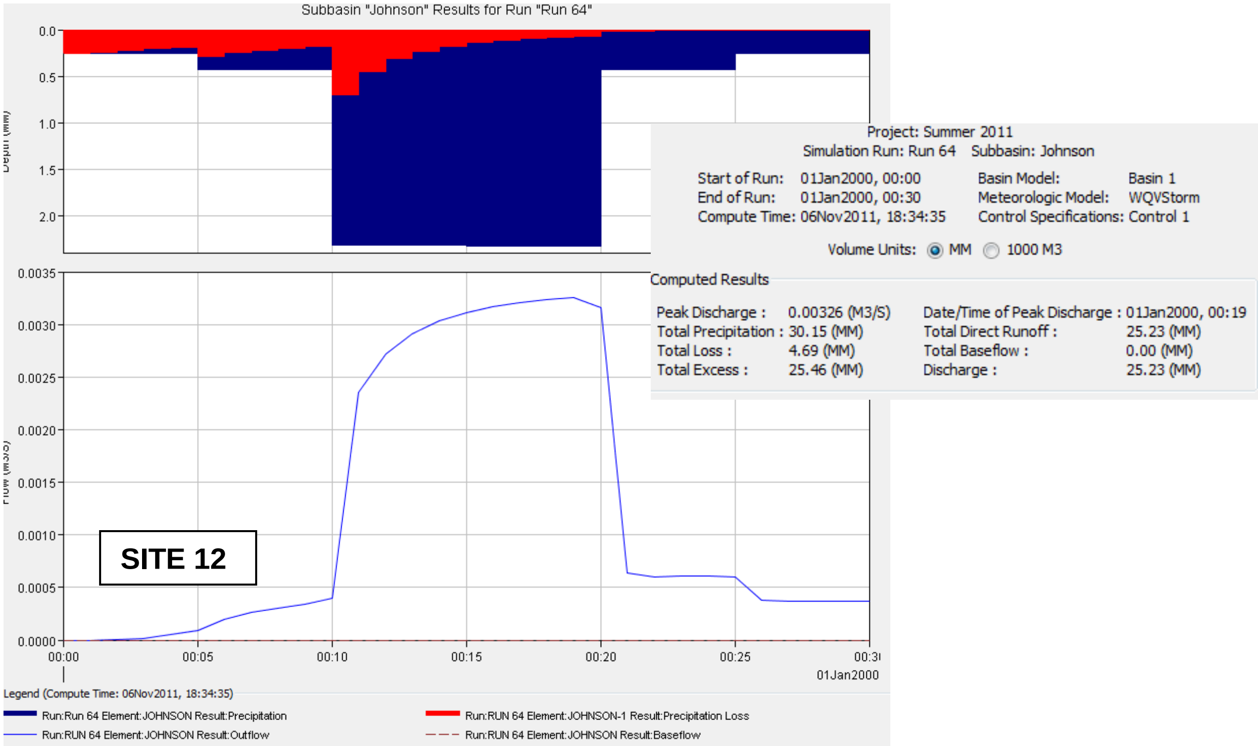
Basin Model: Basin 1
Meteorologic Model: WQVStorm
Control Specifications: Control 1

Volume Units: ● MM ○ 1000 M3

Computed Results

Peak Discharge : 0.00260 (M3/S)
Total Precipitation : 30.15 (MM)
Total Loss : 4.69 (MM)
Total Excess : 25.46 (MM)

Date/Time of Peak Discharge : 01Jan2000, 00:19
Total Direct Runoff : 25.28 (MM)
Total Baseflow : 0.00 (MM)
Discharge : 25.28 (MM)



Project: Summer 2011
Simulation Run: Run 64 Subbasin: Johnson

Start of Run: 01Jan2000, 00:00
End of Run: 01Jan2000, 00:30
Compute Time: 06Nov2011, 18:34:35

Basin Model: Basin 1
Meteorologic Model: WQVStorm
Control Specifications: Control 1

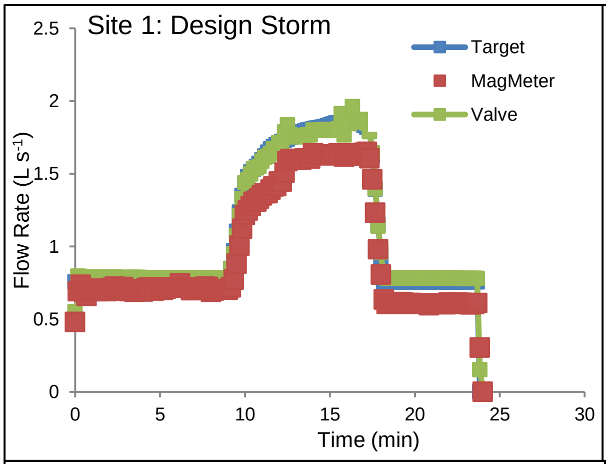
Volume Units: ● MM ○ 1000 M3

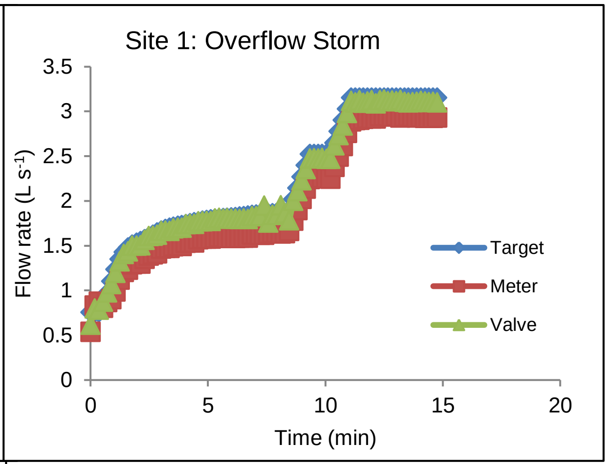
Computed Results

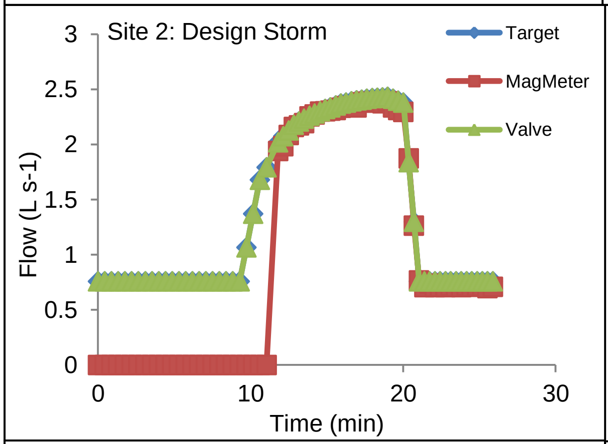
Peak Discharge : 0.00326 (M3/S)
Total Precipitation : 30.15 (MM)
Total Loss : 4.69 (MM)
Total Excess : 25.46 (MM)

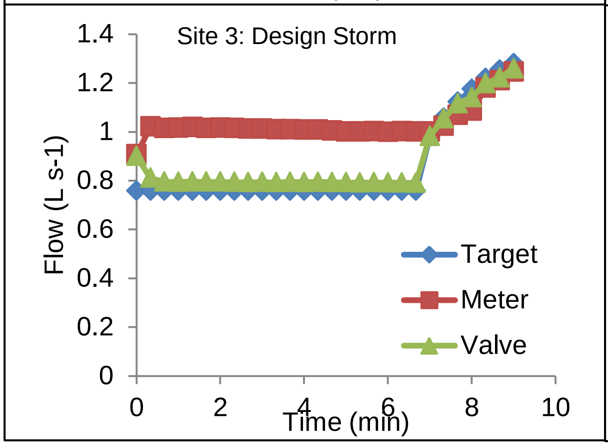
Date/Time of Peak Discharge : 01Jan2000, 00:19
Total Direct Runoff : 25.23 (MM)
Total Baseflow : 0.00 (MM)
Discharge : 25.23 (MM)

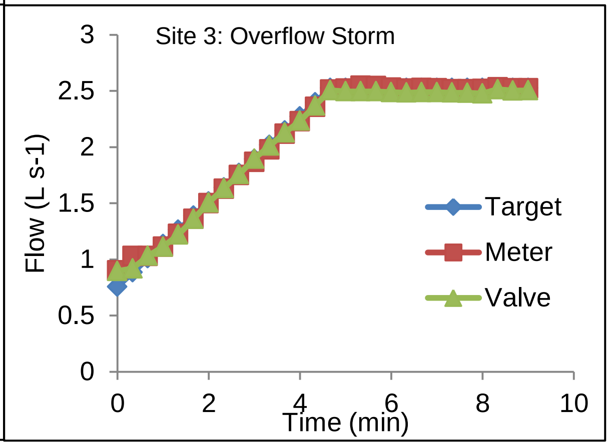
Appendix E: Simulation Hydrograph Data

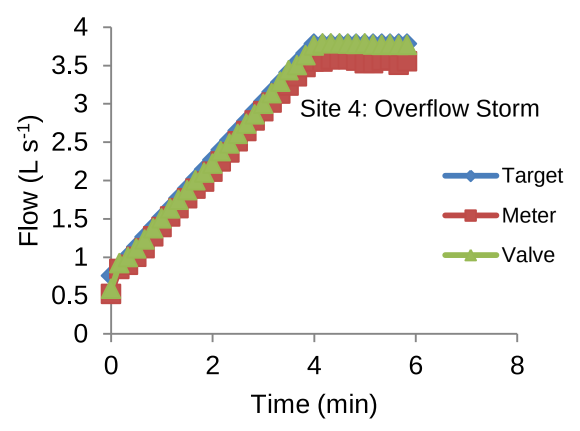


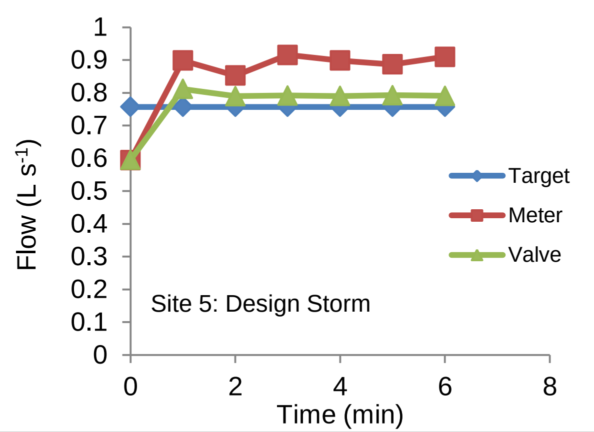


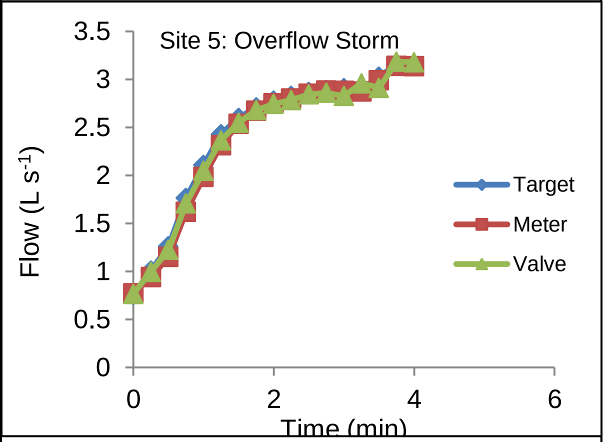


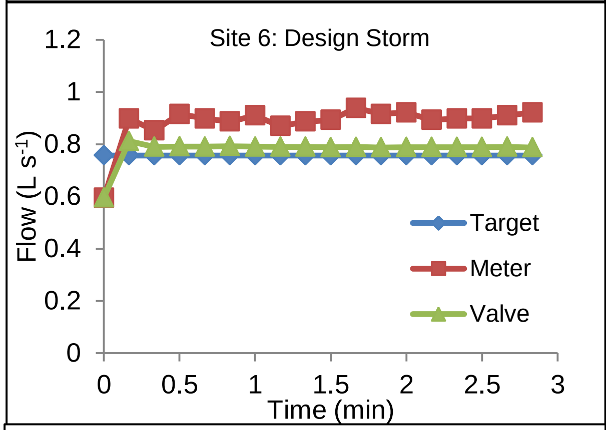


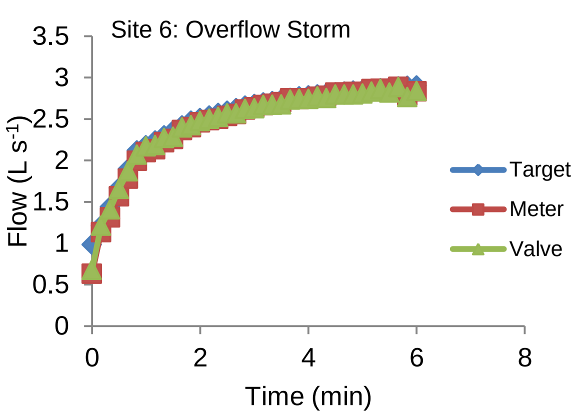


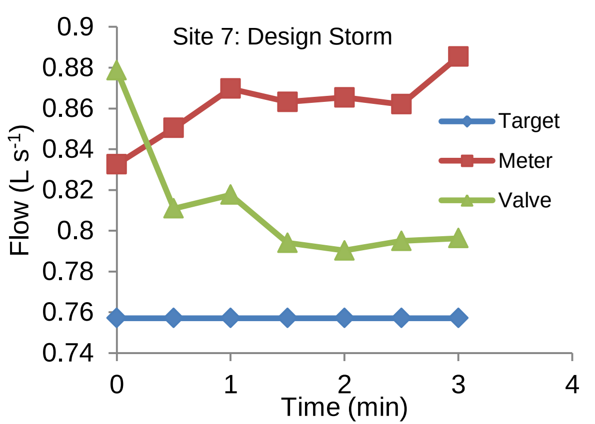

Site 4: Overflow Storm
Flow (L s-1)
Time (min)
0
0.5
1
1.5
2
2.5
3
3.5
4
0
2
4
6
8
Target
Meter
Valve

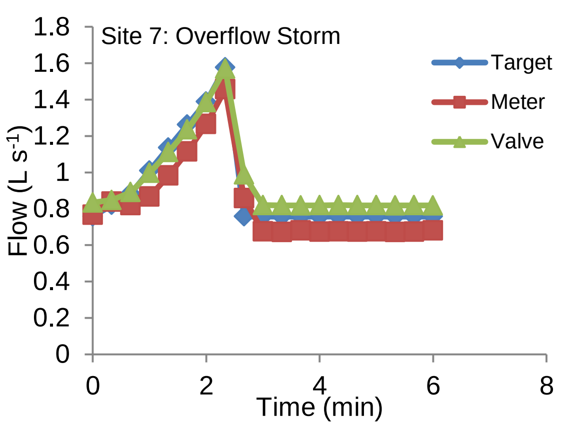

Site 5: Design Storm
Flow (L s-1)
Time (min)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
2
4
6
8
Target
Meter
Valve

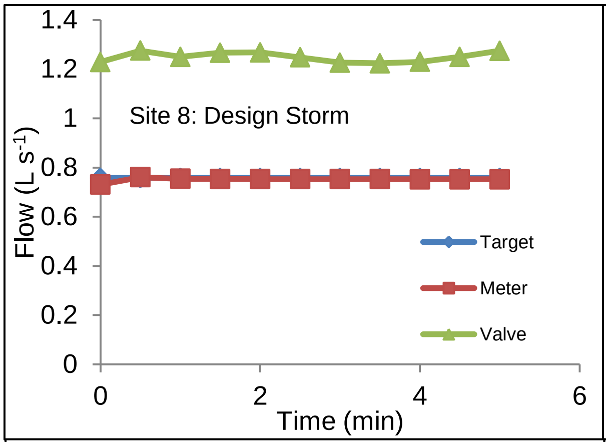

Site 5: Overflow Storm
Flow (L s-1)
Time (min)
0
0.5
1
1.5
2
2.5
3
3.5
0
2
4
6
Target
Meter
Valve

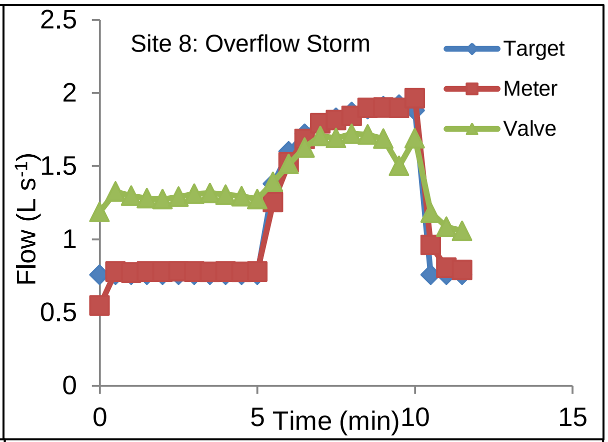

Site 6: Design Storm
Flow (L s-1)
Time (min)
0
0.2
0.4
0.6
0.8
1
1.2
0
0.5
1
1.5
2
2.5
3
Target
Meter
Valve

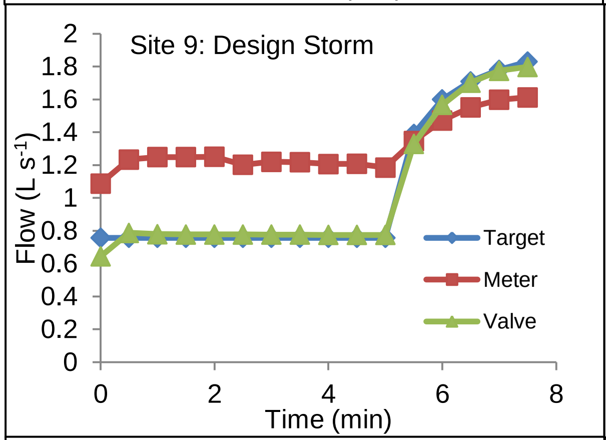

Site 6: Overflow Storm
Flow (L s-1)
Time (min)
0
0.5
1
1.5
2
2.5
3
3.5
0
2
4
6
8
Target
Meter
Valve

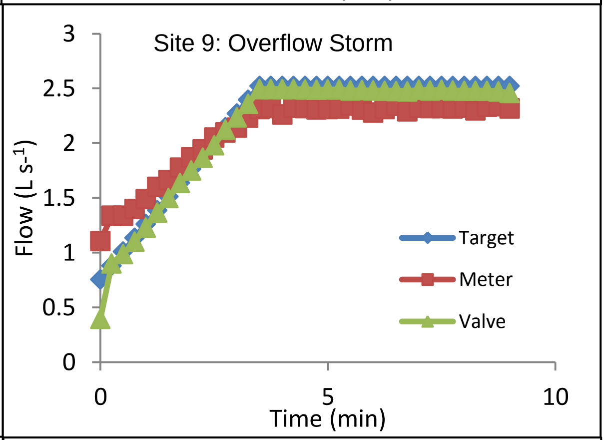

Site 7: Design Storm
Flow (L s-1)
Time (min)
0.74
0.76
0.78
0.8
0.82
0.84
0.86
0.88
0.9
0
1
2
3
4
Target
Meter
Valve

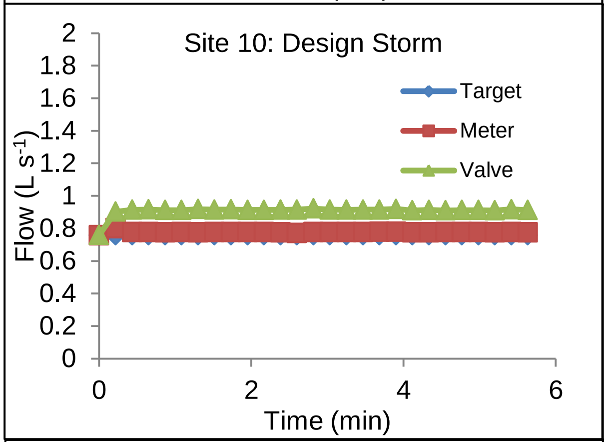

Site 7: Overflow Storm
Flow (L s-1)
Time (min)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
0
2
4
6
8
Target
Meter
Valve

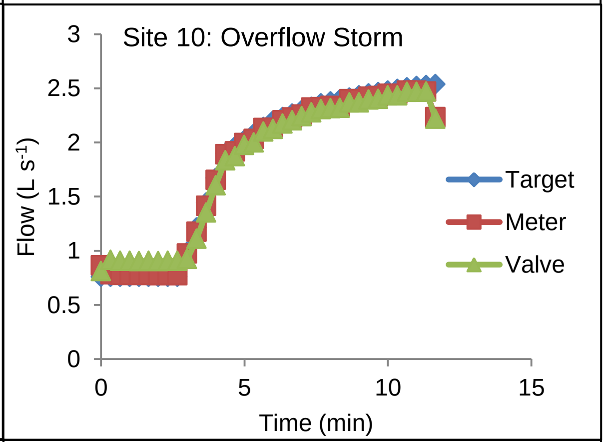

Site 8: Design Storm
Flow (L s-1)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
2
4
6
Time (min)
Target
Meter
Valve

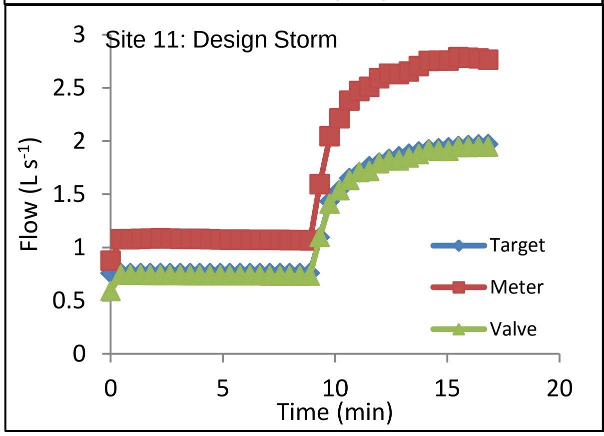

Site 8: Overflow Storm
Flow (L s-1)
2.5
2
1.5
1
0.5
0
0
5
10
15
Time (min)
Target
Meter
Valve

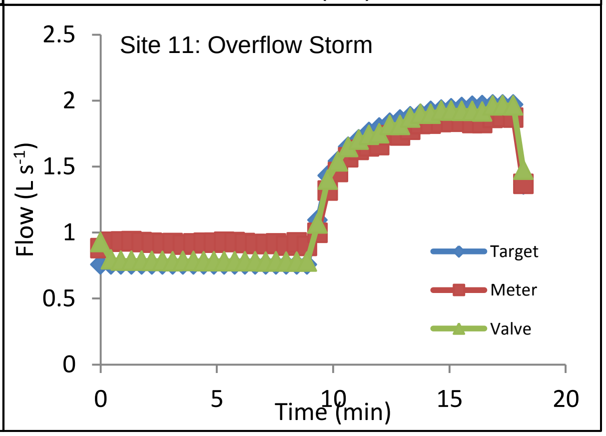

Site 9: Design Storm
Flow (L s-1)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
2
4
6
8
Time (min)
Target
Meter
Valve

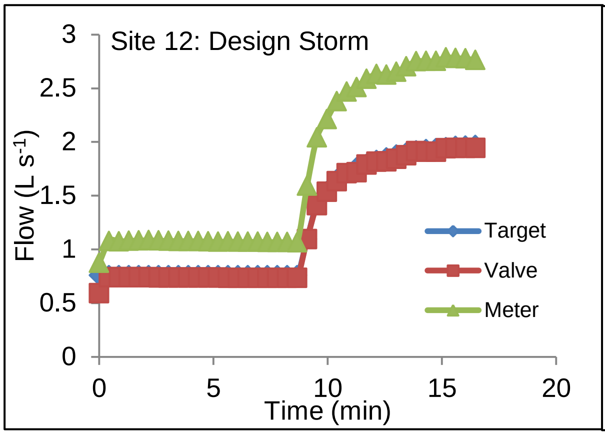

Site 9: Overflow Storm
Flow (L s-1)
3
2.5
2
1.5
1
0.5
0
0
5
10
Time (min)
Target
Meter
Valve

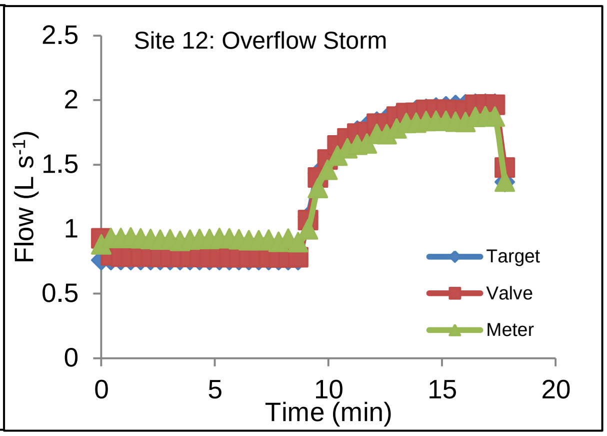

Site 10: Design Storm
Flow (L s-1)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
2
4
6
Time (min)
Target
Meter
Valve


Site 10: Overflow Storm
Flow (L s-1)
3
2.5
2
1.5
1
0.5
0
0
5
10
15
Time (min)
Target
Meter
Valve


Site 11: Design Storm
Flow (L s-1)
3
2.5
2
1.5
1
0.5
0
0
5
10
15
20
Time (min)
Target
Meter
Valve


Site 11: Overflow Storm
Flow (L s-1)
2.5
2
1.5
1
0.5
0
0
5
10
15
20
Time (min)
Target
Meter
Valve

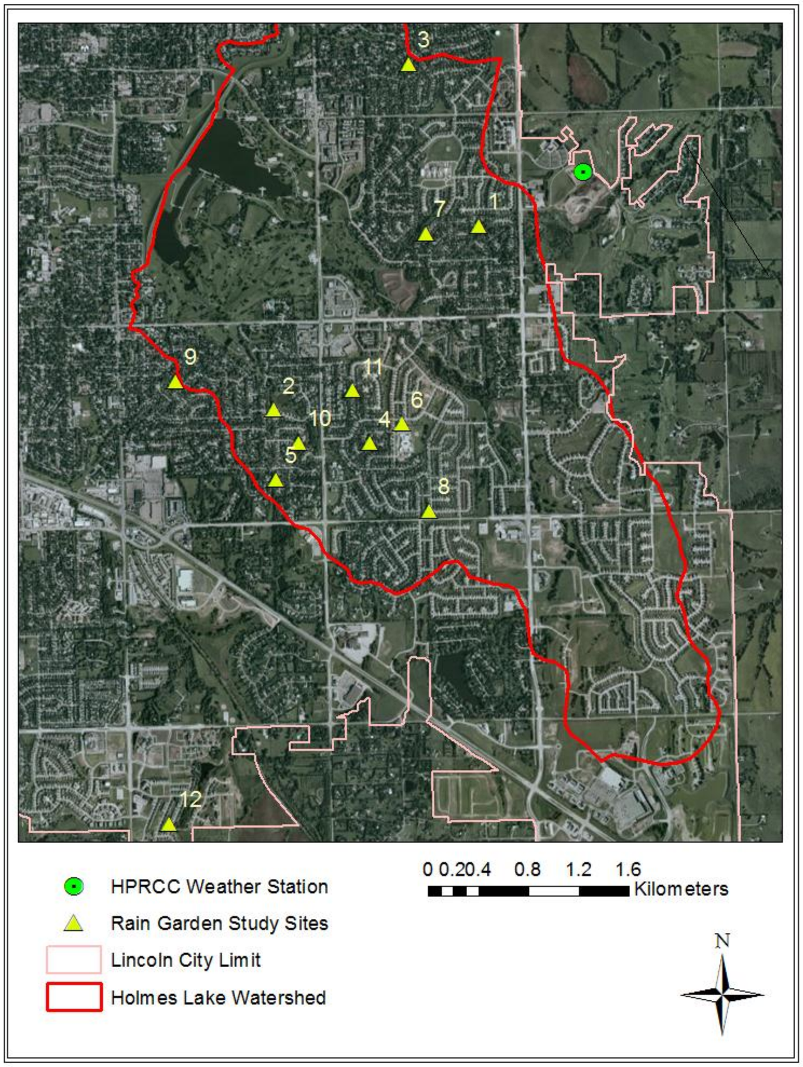




Site	Nash-Sutcliffe Efficiency				Peak Flow Rate (L s^{-1})				Volumetric Percent Error from Target (%)			
	WQV		*Overflow*		*WQV*		*Overflow*		*WQV*		*Overflow*	
	Meter	Valve	Meter	Valve	Meter	Target	Meter	Target	Meter	Valve	Meter	Valve
1	0.945	0.999	0.894	0.996	1.65	1.86	2.95	3.15	12.2	1.2	10.1	1.2
2	0.996	0.996	n/a	n/a	2.39	2.43	n/a	n/a	25.5	.07	n/a	n/a
3	-8.96	0.924	0.999	0.999	1.24	1.28	2.55	2.52	20.5	3.2	.002	.75
4	n/a	n/a	0.968	0.999	n/a	n/a	3.58	3.79	n/a	n/a	6.2	.73
5	-0.778	-0.02	0.998	0.999	.916	.757	3.14	3.15	12.4	1.2	2.0	1.3
6	-3.02	-0.26	0.997	0.999	0.94	0.76	2.89	2.90	16.7	3.0	2.5	1.9
7	-47.11	-3.61	0.814	0.920	0.89	0.76	1.46	1.58	6.1	7.2	8.4	5.2
8	-667.4	-0.65	0.879	0.997	1.28	0.76	1.72	1.92	65.0	.73	18.8	.28
9	-5.12	0.992	0.938	0.997	1.61	1.83	2.34	2.52	25.6	.28	3.5	1.9
10	-26.4	-10.6	0.991	0.997	0.92	0.76	2.47	2.54	20.0	2.6	1.1	1.4
11	0.451	0.996	0.895	0.994	2.79	1.97	1.87	1.97	42.0	1.93	2.4	.76
12	0.984	0.994	0.997	0.999	2.96	3.11	3.12	3.26	2.55	.44	3.8	.76

Appendix F: Site Geographic Information

Site ID	Homeowner Last Name	Latitude (° N)	Longitude (° W)
1	Kotrous	40.776375	96.61018
2	Bausch	40.7636861	96.6297
3	Jewel	40.788	96.61613
4	Nicolai	40.7609611	96.62097
5	Ansorge	40.7584917	96.62958
6	Reif	40.7624028	96.61769
7	Loftin	40.7758694	96.61503
8	Cotton	40.7559306	96.61565
9	Matkin	40.76587778	96.63909444
10	Dombrowski	40.76106389	96.62756667
11	Jacobsen	40.76472778	96.62236389
12	Johnson	40.73400556	96.640775



Appendix G: Site Pictures

SITE 1

Figure 27,. Rain garden shown when full of water.

Figure 28. Floating mulch near stilling well and staff gage.

NO PICTURE AVAILABLE FOR SITE 2

SITE 3

Figure 29. View of rain garden with valve and meter delivery system in background. Note white stilling well is installed at surveyed low-point.

Figure 30. Full rain garden characterized by floating mulch. Overflow can be seen in foreground (see arrow),

SITE 4

Figure 31. Densely vegetated rain garden with downspout shown as influent water source.

Figure 32. Full rain garden with outflow escaping over grass berm. Stilling well and staff gage also shown.

SITE 5

Figure 33. Rain garden installed on steep slope more than 30 ft. from downspout. Note heavily rock-armored overflow weir

Figure 34. Improper outflow location observed, leading to mulch and soil erosion .

SITE 6

Figure 35. Rain garden connected to roof by buried black corrugated pipe emerging at the top slope of the cell. Insert photo shows closer look at inlet, which shows evidence of scour and sedimentation. Note the severe slope of the yard, which poses a challenge to residential rain garden performance.

Figure 36. Influent from the simulator system is shown entering through the burlap sack (used for erosion control). Note the hydraulic flow path to outlet indicates poor retention.

SITE 7

Figure 37. Rain garden close to the foundation which receives influent from vine-covered downspout on brick wall. White pipe directs water leaking from valve out of garden before test is conducted.

Figure 38. Stilling well containing transducer as well as staff gage. Slightly more than 0.1 ft. of ponding is occurring

SITE 8

Figure 39. Bird's-eye-view photograph of full rain garden just after simulation was stopped pending overflow.

Figure 40. Data collection devices at the inlet of the rain garden. The inlet is a pop-up riser inlet conveying roof runoff.

SITE 9

Figure 41. Rain garden constructed against residential foundation (out of picture left). Downspout empties just left of large flagstone piece.

Figure 42. Inundated garden showing widespread outflow onto driveway (designed outflow structure is on opposite side of garden).

SITE 10

Figure 43. Previous rockbed and water feature converted to a rain garden. Poor berm definition and lack of berm near the driveway characterize this site.

Figure 44. "Full" garden showing overflow across the berm near the designed outlet. Note: overflow had occured in numerous other spots before this, indicating inappropriate

SITE 11

Figure 45. Rain garden at bottom of steep yard slope, not connected to downspout flow. Note large amounts of shade present.

Figure 46. Upslope view of rain garden with simulation equipment.

SITE 12

Figure 47. Inundated rain garden hugging foundation of home. Two roof downspouts contribute influent flow on either side of the garden.

Figure 48. Floating mulch (characteristic of almost every garden) and water lapping against berm face. Transducer and staff gage in background.

Appendix H: Letter to Rain Home Owners

Date: May 19, 2011

To: **Rain Garden Home Owners**

From: **Dr. Tom Franti**
Biological Systems Engineering
University of Nebraska-Lincoln
402-472-9872 Cell 402-440-4775
email: tfranti@unl.edu

Thank you for agreeing to let us use your rain garden for our experiments this summer.

We are in the process of preparing our equipment and experimental methods. We hope to begin our study the first week of June.

We will be studying ten (10) gardens this summer and are not certain when we will visit your garden, but we will contact you beforehand. We expect to be working until Mid-August, so some gardens will be done later in the summer.

There are several things you should be aware of:

1. We will be digging or probing into the soil (very small holes) so will need to contact *Diggers Hotline of Nebraska* before we can do this. They may place small flags on your lawn to indicate the location of buried utilities.
2. If you have buried lawn sprinkler lines near your rain garden, please mark the location or let us know, so we don't damage them.

3. We will conduct a survey of the rain garden, so will walk about your lawn to do this.
4. When conducting the experiments we will have trucks and trailers parked in the street in front of your house. *If possible, have the street near your rain garden clear of vehicles*. We will remove our trucks and trailers each day. We will be running a small engine-powered generator and water pump.

5. We will have hoses and other equipment running across your lawn.
6. If you have a lawn care service please inform them when we are there so they don't arrive to find they cannot do their job because we are on the lawn.

7. We will have a large hose running from the nearest fire hydrant. We may need to place this hose in the street or in front of your driveway or your neighbor's driveway; it will be possible for you to drive over the hose.
8. Finally, we will replace or repair any damage to your rain garden, such as soil erosion or plant damage.

If you have any questions do not hesitate to call my phone number listed above, or send me an email.

Appendix I: Pilot Rain Garden Evaluation Executive Summary

DRAFT 2

Rain Garden Hydrologic Evaluation:

Antelope Park Church of the Brethren

3645 Sumner
Lincoln, NE 68506

University of Nebraska-Lincoln

Lead Researchers:

Thomas Franti, PhD, P.E., Extension Engineer
David P. Shelton, Extension Engineer
Andrew Anderson, Masters Student
Alan Boldt, Research Engineer

Executive Summary

A hydrologic evaluation of the rain garden on the property of Antelope Park Church of the Brethren in Lincoln, NE was conducted on September 20 and 30, 2010. The lead researchers of the study are Dr. Thomas Franti and Professor David Shelton of the University of Nebraska-Lincoln, environmental engineering master's student Andrew Anderson, and research engineer Alan Boldt. This research project is being done to assess the hydrology of existing rain gardens built primarily during the Holmes Lake Water Quality Improvement Program around 2007. Established standards were used for these installations, but were adjusted to improve drainage of the high clay/low infiltration soils found around the city. The church rain garden played the role of a pilot assessment to test and confirm evaluation protocol before assessing another ten rain gardens in the summer of 2011.

The most significant findings of the hydrologic study are:

- Rain garden adequately handles the 90% cumulative probability event (i.e. "Water Quality" storm of 0.8 inches).
- The rain garden appears to be oversized.
- The amended garden soil infiltrates exceptionally well.
- The berm structure successfully overflows at the designed location

Additionally findings are:

- Plant selection and spatial placement is consistent with local rain garden recommendations.
- Antecedent soil moisture did not appear to have a dramatic effect on rain garden holding capacity.

The following table highlights some physical parameters of the site

Total Catchment Area	2560 ft^2
Roof	1367 ft^2
Lawn	1192 ft^2
Area of Garden	232 ft^2
Soil Texture	Silt Loam
Bulk Density, Avg.	1.03 $g \cdot cm^{-3}$
Organic Matter, Avg	10.4%
Infiltration rate during fill, Avg	36.5 $cm \cdot hr^{-1}$
Water volume before overflow	900 gal

Simulator

A 500 gallon tank mounted on an 18’ trailer was used to distribute the water to the rain garden. The water was obtained from the fire hydrant adjacent to Normal Blvd on the south side of the property. This water was used to produce a controlled flow into the rain garden’s rock-covered inlet. The flow was controlled through a valve operated from a laptop and computer simulation program, and was specifically meant to mimic the flow produced by a typical urban Midwestern-style storm with a volume of eight-tenths of an inch, the standard design volume for rain gardens in Eastern Nebraska. (UNL Extension, 2009)

Simulator setup in parking lot (9/23/10)

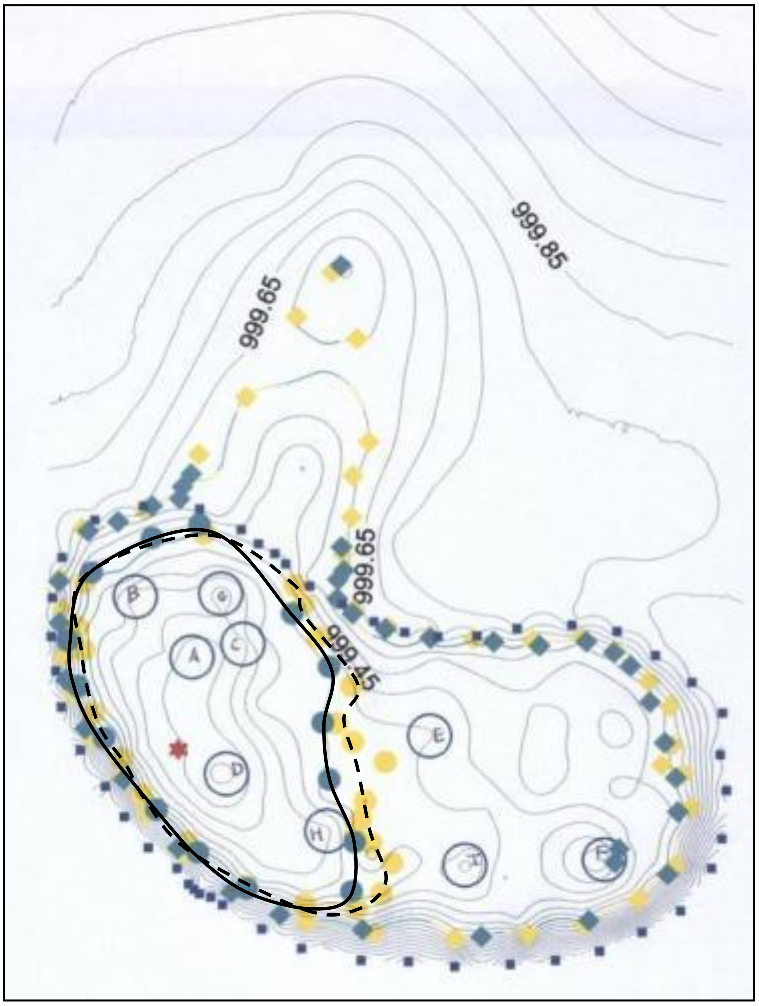
Flow meter/valve delivery system at inlet(9/23/10)

Water height was measured from the lowest point in the rain garden using both a manual gage and a pressure transducer. Using surveyed data of the rain garden, the research group was able to extrapolate volumes from any given gauge height.

Test Results

The test was done on two separate days with the idea that test day 1 would be with “dry soil conditions” followed by a one day gap, and a subsequent day 2—“wet soil conditions” testing. Due to weather restrictions, we had to artificially wet the garden with a hose before test day 2, which was delayed by 4 days.

Each day consisted of two simulation runs—one “water quality” (0.8 inch) event hydrograph followed by a run meant to fill up the entire garden before overflow was witnessed. The furthest advance of water was marked with flags for all four events, and represents the perimeter of the maximum ponded depth. The photo below shows the various colored flags marking the ponded water outline. These flags were surveyed and are shown together in the figure below (left). Evident in the left figure is the similarity in water depth reached by both water quality events. This indicates that antecedent moisture of the soil did not have a dramatic effect on surface storage capacity. An important thing to note is that only about half the garden was filled by the design storm.



———	Design Storm Event – Day 1
- - - -	Design Storm Event – Day 2

●	Day 1 WQV
◆	Day 1 Overflow
●	Day 2 WQV
◆	Day 2 Overflow

Topographic map of rain garden showing outlined design storm maximum ponded front.

Based on the simulations over two days, the following conclusions were made:

1. **Rain garden adequately handles the 90% cumulative probability event (i.e. “Water Quality” storm of 0.8 inches).**

As can be seen in the topographic map on the previous page, both design storms reached a maximum depth that covered only about half of the garden’s size. This indicates that the garden is functioning correctly as a stormwater retention structure, potentially preventing that water from running off onto impervious surfaces south of the property. This indicates the garden structure is doing its part to reduce the volume of stormwater entering Antelope Creek. Benefits of this include decreased erosion potential, increased water quality, and curbing the City’s stormwater infrastructure load during a rain event.

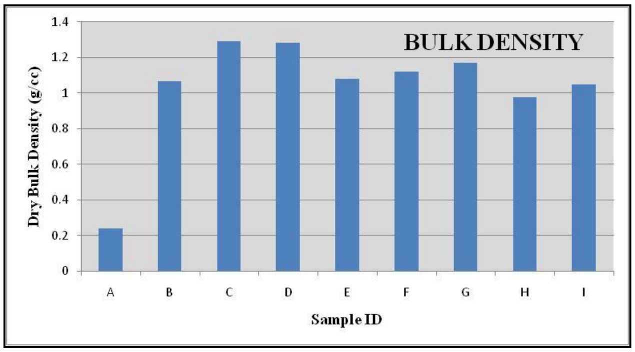
2. **The rain garden appears to be oversized.**

While it is clear the garden functions in capturing the design storm volume of 0.8 inches, it is also clear that the garden may not need to be 232 ft^2 to do so. As evident in the topographic map on the previous page, the water quality event utilized only half the garden’s surface area. This translates into a utilization of only about 40% of the total potential storage volume. UNL’s

A smaller garden would incur less upfront cost and maintenance, while still holding the design volume.

3. **The amended garden soil infiltrates exceptionally well**

The University of Nebraska-Lincoln’s publication “Stormwater Management: Rain Garden Design for Homeowners” recommends proper functioning rain gardens infiltrate 0.25 inches of water per hour or greater. Based on a water balance calculation of infiltration during the water quality event simulation, the garden infiltrated at a rate between 8.5 in/hr (21.63 cm/hr) and 21 in/hr (53.62 cm/hr). This represents almost a 6,000% increase over the minimum required infiltration called for by the NebGuide publication. This rapid infiltration is attributed to the highly porous, high organic matter silt loam soil found in the garden. Specifically, a soil test showed 27% sand, 50% silt, and 23% clay content. It also revealed the garden’s soil to content about 10% organic matter, which helps explain the fast infiltration. Nine soil sample bulk density results further support the fast infiltration seen. (Excluding the outlier, values ranged from 1.05-1.3 g/cm^3



4. The berm structure successfully overflows at the designed location

The rain garden was filled up to a point when the researchers determined overflow over the south berm was occurring. The stone-covered outlet structure was indeed the location at which the researchers first observed flowing water. (See picture on following page).

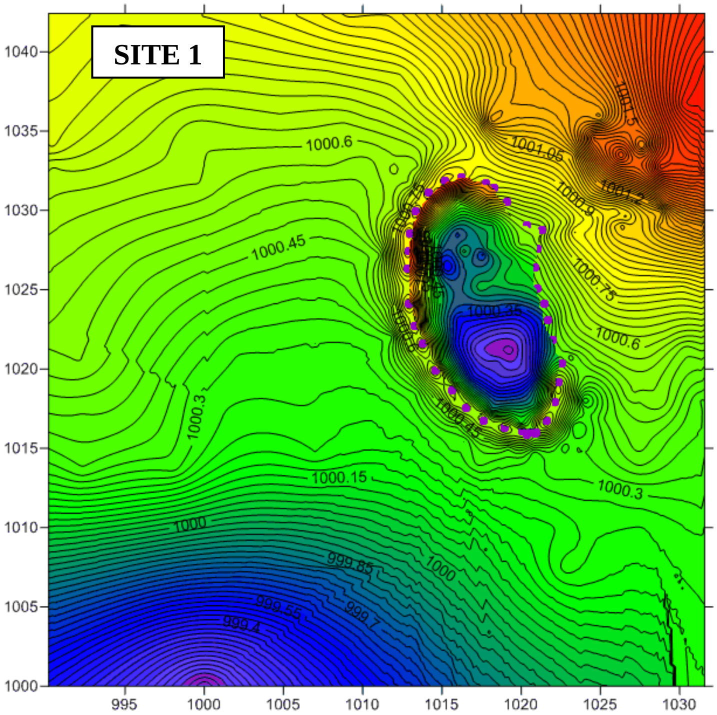
Rock-protected berm outlet (south side) showing overflow seepage.

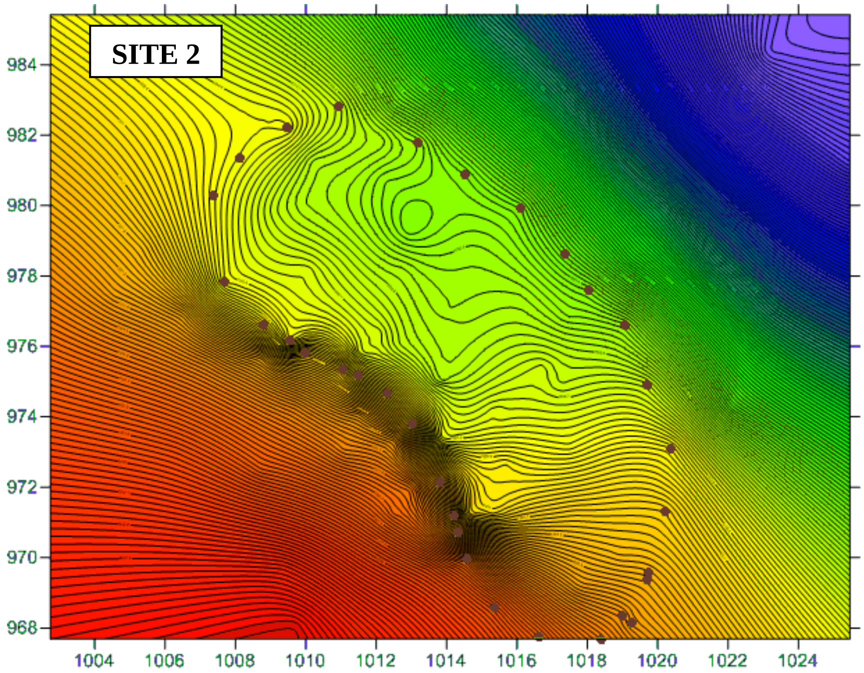
An interesting point to note is that before overflow was observed at the design location, water had backed up into the turf area north of the garden (see the topographic map shown previously). This indicates that the initial design grading of the garden did not ensure that all water would be contained. However, the backed-up pool of water does not appear to be dangerously close to the church foundation as to be a cause for alarm.

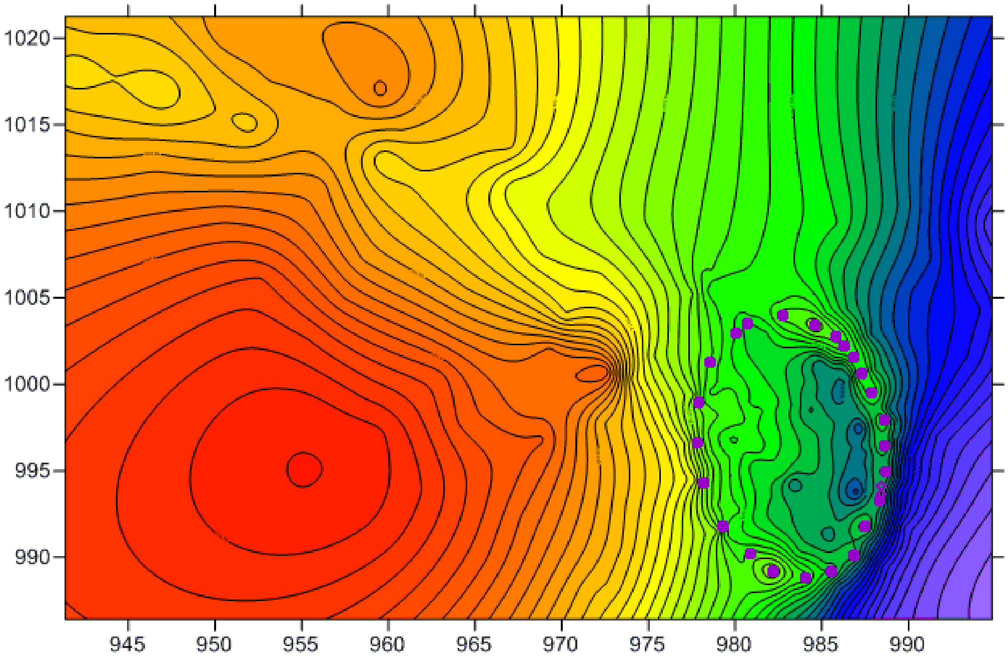
Acknowledgements

The researchers would like to thank Antelope Park Church of the Brethren for providing a rain garden for the simulator pilot project in September of 2010.Valuable lessons were learned and will be applied to the summer simulations in 2011. Special thanks go to John Doran for establishing a site for the researchers to initiate their rain garden study.

Appendix J: Contour Maps of Rain Gardens



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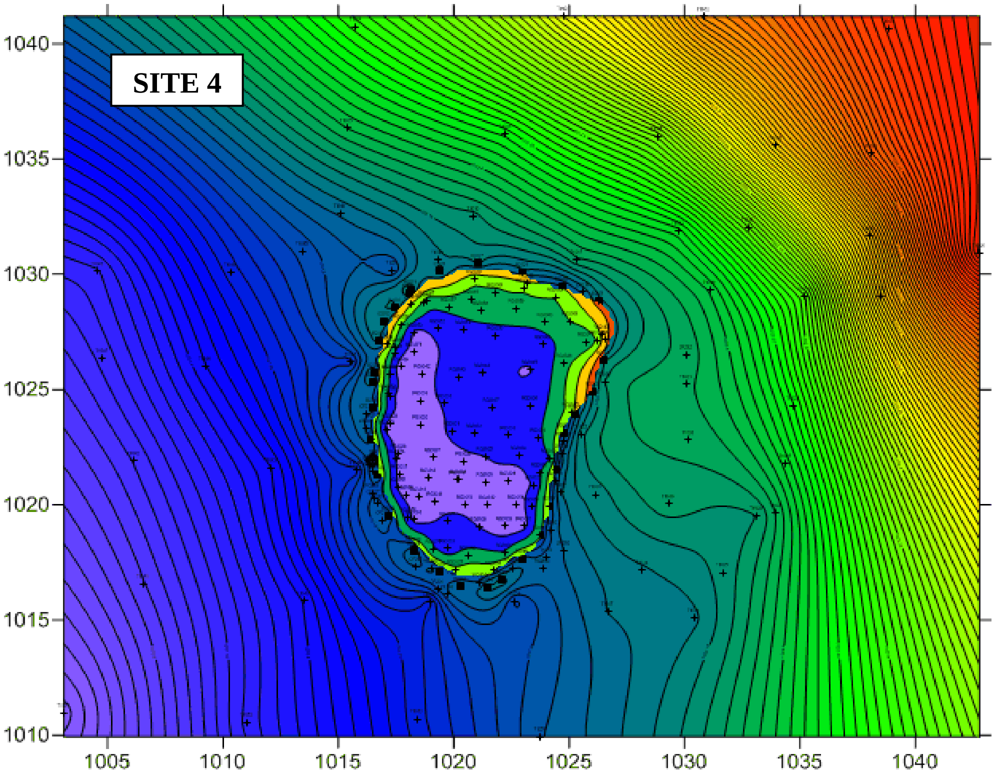
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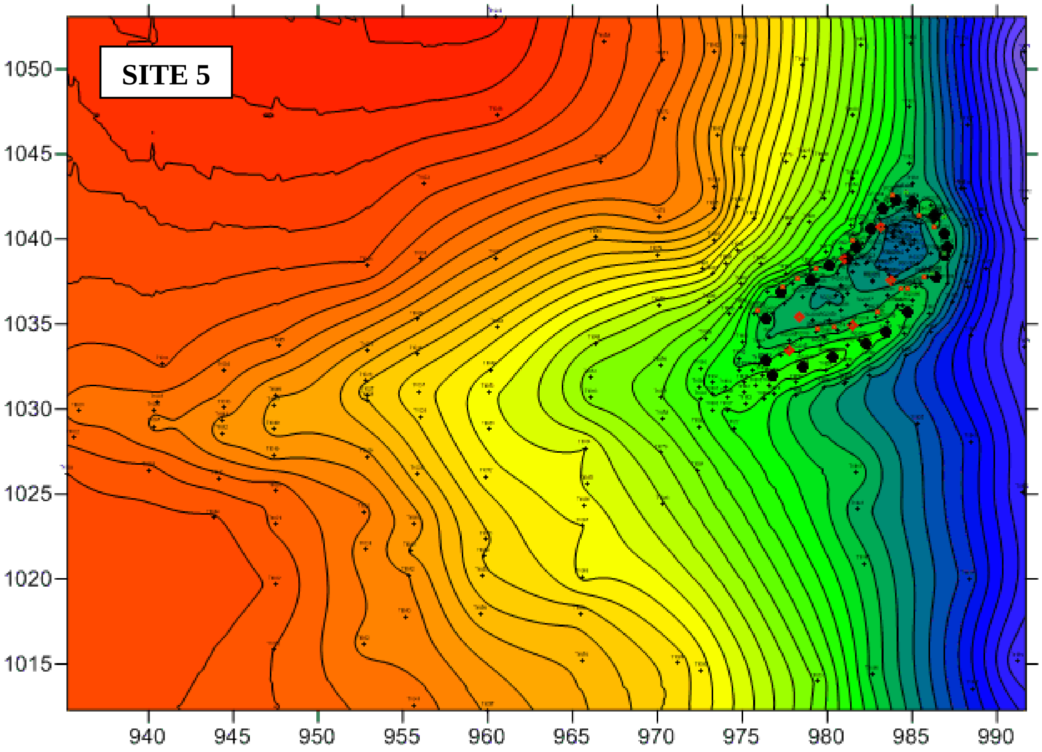
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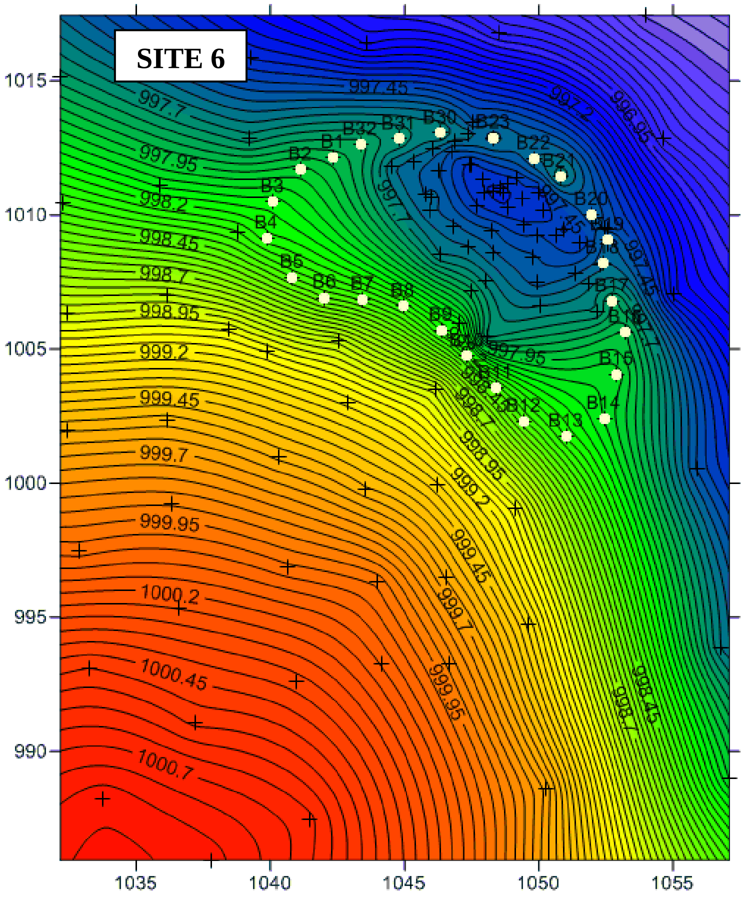
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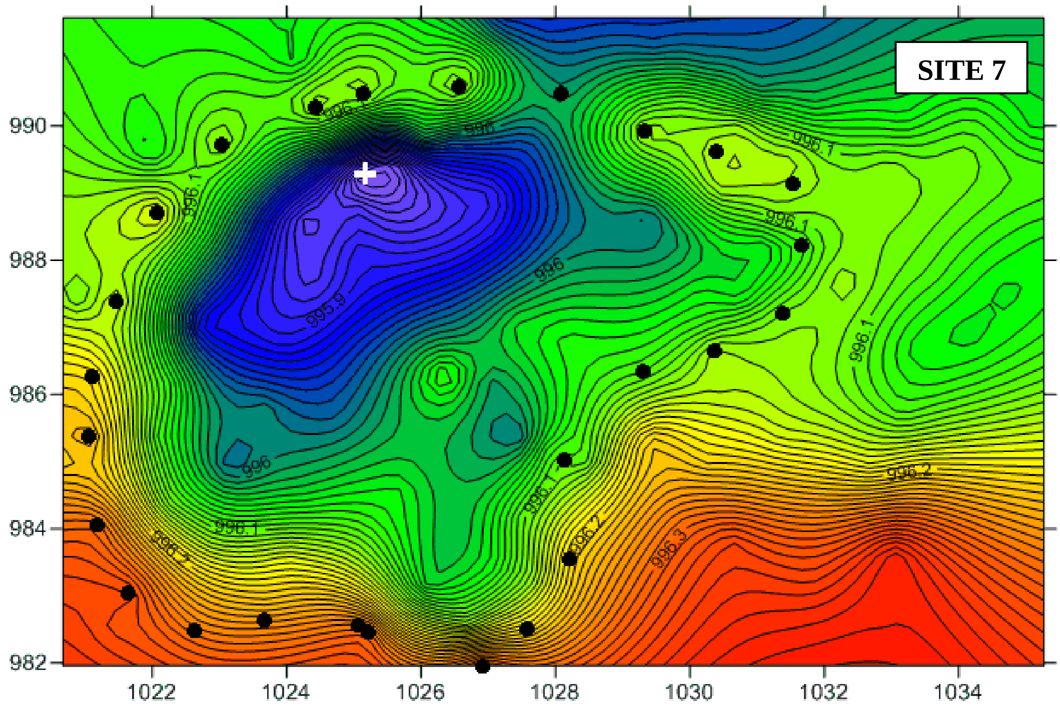
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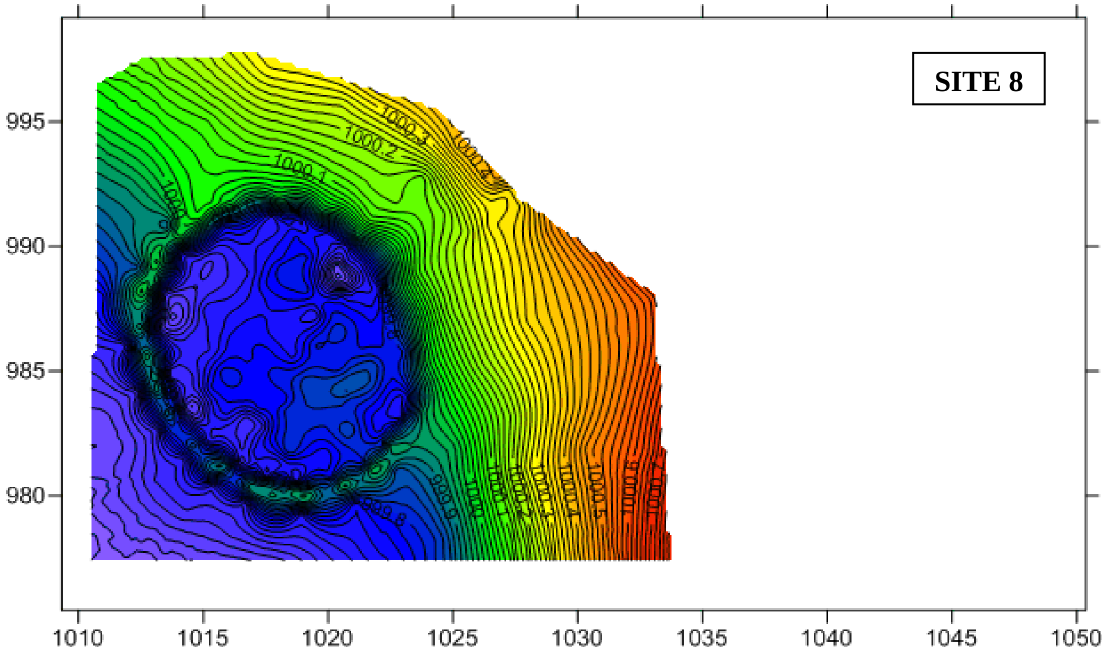
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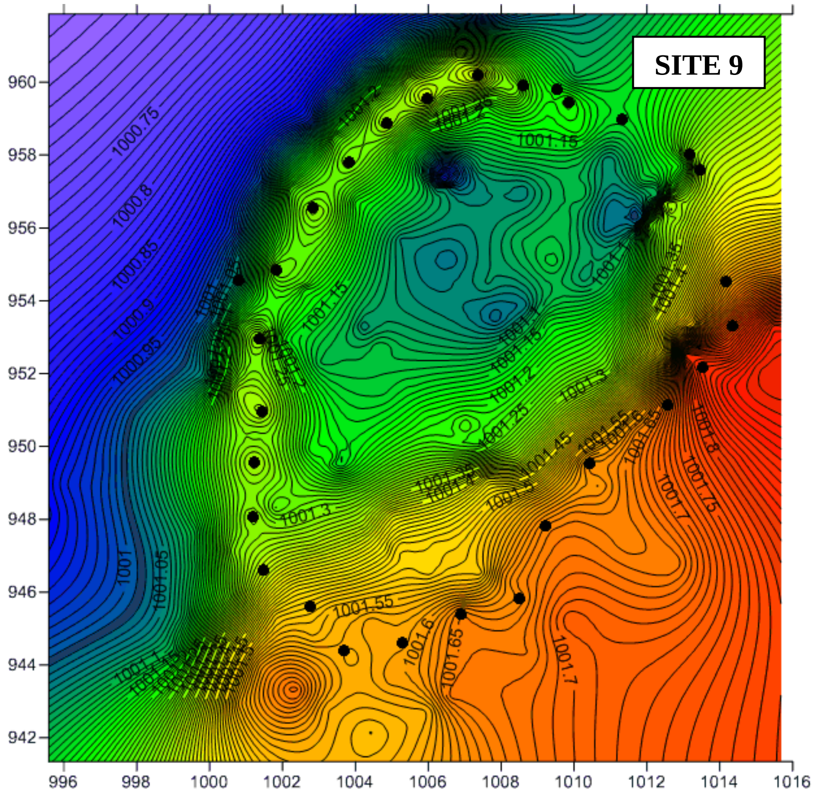
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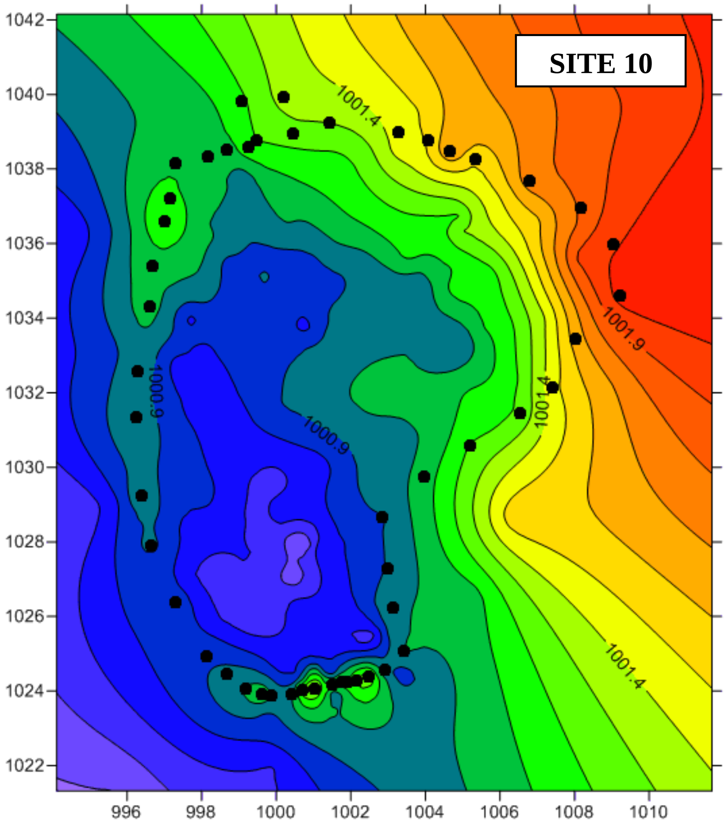
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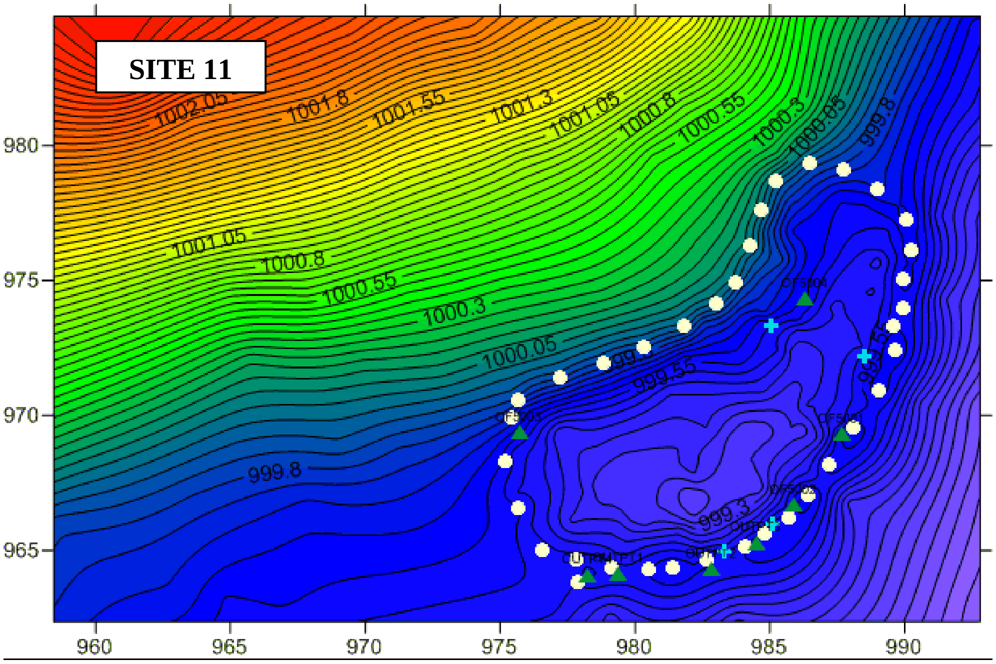
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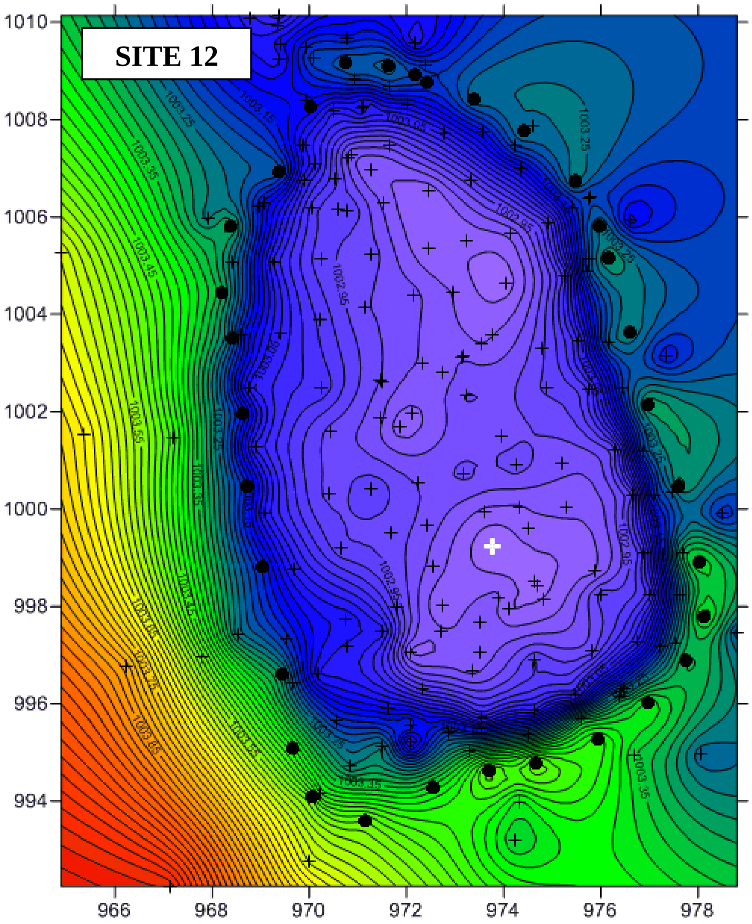
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Appendix K: Minimum Infiltration Rate Value Normality Test

1. Unmodified Infiltration Rate Data

x (min. infil. Rate for design storm)	Z value	f(x)	F(x)
0.18	-0.6665	0.012	0.2525
0.38	-0.6590	0.012	0.2549
0.4	-0.6583	0.012	0.2552
1.37	-0.6219	0.0123	0.2670
3.65	-0.5364	0.0130	0.2958
4.13	-0.5184	0.0131	0.3021
4.98	-0.4865	0.0133	0.3133
16.2	-0.0658	0.0149	0.4738
28	0.3767	0.0139	0.6468
67.8	1.8692	0.0026	0.9692
70.4	1.9667	0.0022	0.9754

Mean = 17.96

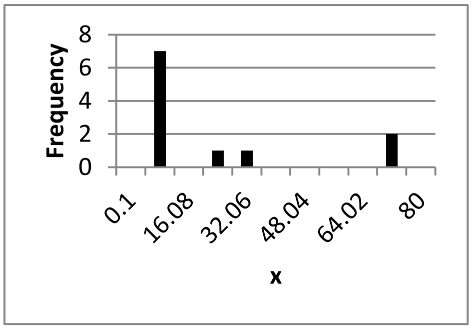
Standard Deviation = 26.67

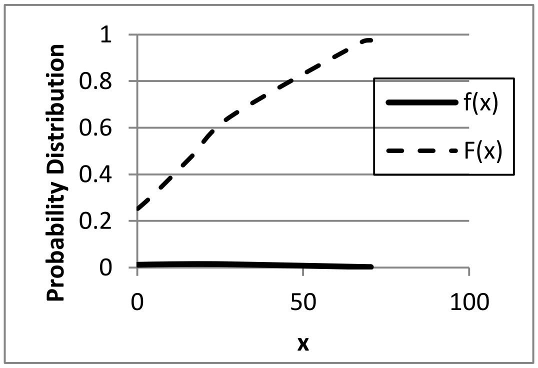
Number of bins = 10

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

$$z = \frac{x-\mu}{\sigma}$$

Bin	Frequency
0.1	0
8.09	7
16.08	0
24.07	1
32.06	1
40.05	0
48.04	0
56.03	0
64.02	0
72.01	2
80	0





<u>Normality Test (performed in SigmaPlot)</u>

Shapiro-Wilkes Parameter = 0.655

P < 0.001

Failed

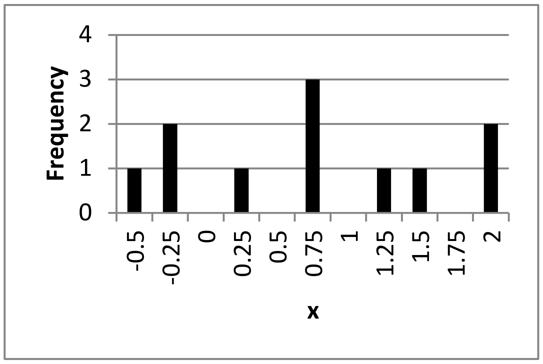
2. Log-Transformed Infiltration Rate Data

x	Z value	f(x)	F(x)
-0.745	-1.5	0.1426	0.067
-0.420	-1.14	0.2288	0.127
-0.398	-1.12	0.2352	0.132
0.137	-0.53	0.3823	0.298
0.562	-0.06	0.4390	0.476
0.616	-0.0009	0.4398	0.50
0.697	0.089	0.4381	0.535
1.210	0.653	0.3552	0.743
1.447	0.92	0.2893	0.82
1.831	1.34	0.1795	0.910
1.848	1.36	0.1752	0.913

Mean x =0.62

Standard Deviation = 0.91

Number of bins = 10



Bin	Frequency
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-0.25	2
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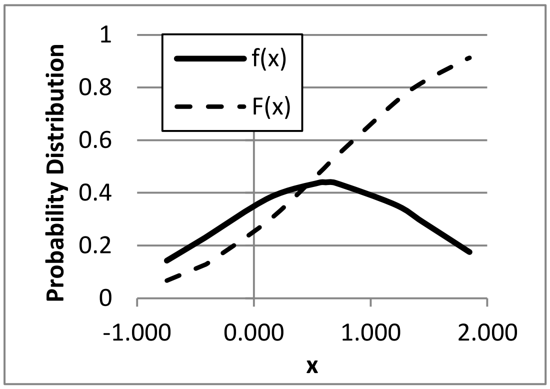
0.25	1
0.5	0
0.75	3
1	0
1.25	1
1.5	1
1.75	0
2	2



Normality Test (performed in SigmaPlot)

Shapiro Wilkes Parameter = 0.925

p = 0.398

Passed