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The development and application of a four-level rain garden assessment methodology

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Abstract

Rain gardens are a commonly used stormwater best management practice (BMP) in urban areas that reduce stormwater runoff volume via infiltration and evapotranspiration and remove pollutants via filtration, sorption, microbial degradation and other processes. In response to the implementation of phase II of the National Pollutant Discharge Elimination System (NPDES) program, small municipal separate storm sewer systems (MS4s) are required to evaluate the effectiveness of their stormwater BMPs. Currently monitoring is the most widely used approach for evaluating the performance of stormwater BMPs, but this approach has many limitations including excessive time, effort, and cost. For the research reported in this manuscript a tiered four level assessment approach was developed consisting of visual inspection, capacity testing, synthetic runoff testing, and monitoring. Several rain gardens were evaluated using this approach. Of the rain gardens assessed eight were functioning properly based on the visual inspection (level 1) and the saturated hydraulic conductivity (K_{sat}) was then measured at several locations throughout the basin. The median values of K_{sat} for each rain garden ranged from 0.0196 to 0.0008 cm/s. This resulted in drain times well below the required 48 hours. The drain time determined by the synthetic runoff tests (level 3) corresponded well with the estimates based on the point measurements, with the exception of one rain garden which contained a restrictive soil layer beneath the topsoil. The results demonstrate that this assessment approach provides effective tools for determining if a rain garden is functioning properly and optimally, for developing maintenance tasks and schedules, and for ensuring due diligence during construction.

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1. Project Overview

The work presented in this report is a product of two stormwater projects. The first project funded by the Minnesota Pollution Control Agency (MPCA) was "Assessment of Stormwater Best Management Practices." This project involved the development and review of techniques to assess the effectiveness of stormwater best management practices (BMPs). The final outcome was a manual aimed to assist municipalities assess their stormwater BMPs. The second project which, funded by the Metropolitan Council Environmental Services (MCES) and Local Road Research Board (LRRB), was "Assessment of Stormwater Treatment Practices on the Quantity and Quality of Runoff." This project involved the development and implementation of new techniques for the testing of underground, proprietary devices, rain gardens, and bio-retention facilities for stormwater treatment. The combination of these two projects and the large scale of the "Assessment of Stormwater Best Management Practices" involved a partnership of several University of Minnesota departments and centers. These partners included: Bioproducts and Biosystems Engineering, Civil Engineering, University of Minnesota Extension, St. Anthony Falls Hydraulic Laboratory, and the Water Resources Center. Several additional partnerships outside of the University of Minnesota were also developed and included: City of Bloomington, City of Plymouth, Dakota County Soil and Water Conservation District, Ramsey Washington Metro Watershed District, Three Rivers District, Washington County Conservation District, and the Wisconsin Department of Natural Resources.

The work presented in this report contributed to the *Assessment of Stormwater Best Management Practices Manual* in several ways. The expertise of rain garden function gained through this research, the development of the four-level assessment approach and the implementation of an assessment program all contributed to the *Assessment of Stormwater Best Management Manual.* The objectives of the manual were to: 1) develop standardized methodology for the assessment of stormwater BMPs, 2) present more accurate methods for flow measurements in stormwater conveyance systems, 3) provide advanced sampling methodology that helps minimize typical sources of bias, 4) present source reduction measures for municipal use, 5) develop standardized inspection checklists, and 6) include specific considerations for categories of stormwater BMPs. These objectives resulted in a web-based manual consisting of thirteen chapters, and five appendices, examples of the implementation of assessment programs, and standardized checklists and reporting forms. The *Assessment of Stormwater Best Management Practices Manual* is located on the project website: http://wrc.umn.edu/outreach/stormwater/bmpassessment/index.html.

2. Introduction

Stormwater runoff is of growing concern in highly urbanized areas due to the associated increase in impervious area. Booth and Jackson (1997) reported that the extent of imperviousness has a direct effect on stream hydrology and water quality and consequently on stream habitat and biota. Increased volumes of precipitation and higher flow rates of runoff that occur with increased urban land has caused the frequency and magnitude of floods to increase and base flows to decrease (Wang et al., 2001). The stormwater runoff entering our surface waters contain various contaminants including nutrients, suspended solids, pathogens, metals, pesticides, chloride and hydrocarbons which come from residential, commercial, and industrial land uses.

In response to the degraded water quality found in our waterways due to these non-point sources, the Clean Water Act requires the regulation of municipal separate storm sewer systems (MS4s) and the implementation of Storm Water Pollution Prevention Programs (SWPPP) in a two-phase program (MPCA, 2001). The SWPPP must include discharge detection and elimination, construction and post construction runoff control, and pollution prevention measures. Key to pollution prevention efforts in urban areas are the installation and maintenance of stormwater BMPs. Currently there is little guidance on how to properly assess the effectiveness of these practices. Low impact development (LID) practices, such as rain gardens and bioretention facilities, are commonly used to infiltrate stormwater to reduce stormwater runoff volume and improve water quality via filtration and other processes. These systems are of gaining increasing interest among MS4s due to their low cost, potential effectiveness and aesthetic properties. The long-term effectiveness of rain gardens, however have yet to be determined. A standard procedure is needed to assess the effectiveness of rain gardens.

LID offers an innovative approach to managing urban stormwater that mimics predevelopment hydrology using techniques that store, infiltrate, evaporate, and detain runoff. These small, cost-effective landscape features not only reduce the need for stormwater infrastructure, but they also encourage public education and participation (Prince George's County 1999). The principles of LID focus on prevention rather than mitigation by managing rainfall as close to the source as possible (Prince George's County, Maryland, 2002). One commonly used LID practice involves the installation of rain gardens (also referred to as bioretention practices) which are a terrestrial-based, water quality and water quantity control process. Rain gardens treat stormwater via a variety of processes including: settling, filtration, adsorption, plant uptake, and microbial degradation (e.g., nitrification) (Prince George's County, Maryland, 2002). The primary process occurring in rain gardens is the capture of rainwater runoff through curb cuts or storm sewer inlet structures and infiltration of the water into the soil. Dietz and Clausen (2005) reported that 98.8% of inflow entering the two study rain gardens monitored in their study left as subsurface flow. This infiltrated water may then recharge the groundwater supply. Some rain gardens may have underdrains for improved infiltration in areas where the native soils have low permeability or in areas where groundwater recharge is not desired. Rain gardens not only provide treatment of stormwater runoff but also provide habitat for small mammals, birds and insects (Prince George's County, Maryland, 2002).

A complete assessment of rain gardens requires a comprehensive evaluation of all of its components: inlet structures, the health and cover of specified vegetation, soil properties including texture, color, moisture content, bulk density and hydraulic properties. Plants play a key role in several stormwater treatment processes including: the collection or capture of rainfall and runoff, transpiration, uptake of water and nutrients through the root system, and decaying vegetation for the production of humus which adsorbs metals and nitrate (Prince George's County, Maryland, 2002). Several studies indicate that highly vegetative landscapes increase infiltration due the influence of high root mass and increased biological activity in the soil (Buttle and House, 1997; Eldridge and Freudenberger, 2005; Halabuk, 2006; Kodešová et al., 2006; Warner and Young, 1991). In addition to their role in stormwater treatment and infiltration plants provide aesthetic value.

Efficient treatment of stormwater runoff by soil processes requires properly functioning and stable soils (Baker et al., 2007). The soils of rain gardens are designed to promote infiltration, support vegetation and adsorb pollutants. Stormwater manuals have various recommendations for the appropriate mixture of sand, topsoil, and compost. Soil properties such as bulk density, texture, porosity, water content, and organic matter content can influence the ability of the soil to infiltrate water (Buttle and House, 1997; Maidment, 1993). The hydraulic conductivity (a measure of a soil's ability to transmit water) is most affected by porosity, pore-size distribution and pore continuity (Maidment, 1993). Properties of the fluid such as density and viscosity also influence the hydraulic conductivity (Hillel, 1998). The presence of large voids (macropores) formed by the shrinking and swelling action of clays, freezing and thawing cycles, decaying roots, erosive action, and biological activity such as earthworms, insects or burrowing animals can also have significant control on the water transmission property of a soil. Macropores range from 1 mm to over 50 mm in diameter and serve as primary paths for infiltration and drainage of water (Hillel, 1998).

Soil properties such as porosity and hydraulic conductivity can change over time therefore changing the rain gardens ability to infiltrate water. These changes can be due to compaction, loss of soil structure, and/or clogging. Soil compaction reduces infiltration rates by reducing the pore space available for water transmission. Soils in rain gardens may become compacted during construction. Post-construction soil compaction only occurs when heavy machinery is used for maintenance or redevelopment of the site. The degree of soil compaction is reflected in its bulk density and as the bulk density of the soil increases, water retention and hydraulic conductivity near saturation decreases (Maidment, 1993). Bulk density is also a useful measurement for calculating the porosity of the soil where particle density is known or can be estimated. Soil structure is the internal configuration of soil particles which make up the soil matrix and affects the content and transmission of air and water in the soil (Hillel, 1998). The loss of soil structure can occur due to: loss of vegetation, chemical reactions, and compaction. Sediment accumulation can result in the clogging of soil pores and the loss of stormwater storage capacity. These soil properties are therefore critical to maintaining a functional rain garden and should be monitored over time.

There are several reasons for assessing the performance of rain gardens including: fulfilling stormwater permit regulatory requirements, scheduling maintenance, construction due diligence and Total Maximum Daily Load (TMDL) studies. The increasing number of TMDLs required for impaired waters may result in the need to quantify the source reduction that rain gardens provide for determining load allocations. In addition to providing necessary information about the current and long-term performance of the rain garden, the data collected in an assessment program can be used to improve design features of future rain gardens. The results of the assessment allow for an improved understanding of the role of the various system components (i.e. soil, plants, etc.) in pollutant removal and volume reduction.

Currently monitoring is the most widely used approach for evaluating the performance of stormwater BMPs (U.S. EPA, 2002). Monitoring of stormwater BMPs typically involves the collection of samples for analysis and the measurement of the water budget of the BMP using weirs, pressure transducers, data loggers and other monitoring equipment. Monitoring of BMPs however, is often impractical due to the excessive time effort, and cost. This is especially true for rain gardens, which are often small ($< 150\ m^2$), simple, low impact BMPs widely distributed throughout urban and suburban neighborhoods. For example, the cost of a typical 1-2 year monitoring study ($100,000) would far exceed the installation cost of a small residential rain garden (< $5,000). It is of interest, therefore, to develop alternative techniques for assessing the performance of rain gardens. Several methods for determining the efficiency of rain gardens to treat stormwater have been developed as part of a four level assessment program (Gulliver and Anderson, 2007):

(1) visual inspection,
(2) capacity testing,
(3) synthetic runoff testing , and
(4) monitoring.

The *visual inspection* of rain gardens includes techniques for estimating the infiltration rate based on soil texture and an inspection checklist to determine if a rain garden is malfunctioning. *Capacity testing* involves the use of permeameters or infiltrometers to make infiltration rate measurements throughout a rain garden. In the reported study several infiltration devices were evaluated, and one device was selected as the best field technique for assessing the infiltration capacity characteristics of rain gardens. *Synthetic runoff testing* utilizes supplied runoff to fill the basin with water to determine an overall drain time of the rain garden. *Monitoring* stormwater BMPs includes the use of inflow and outflow measurement devices and in most cases the sampling of stormwater runoff for pollutants. While the monitoring of rain gardens for comprehensive watershed studies may be desired in some instances, this fourth level of assessment was not included in the study reported herein.

The main goal of this research was to develop a relatively rapid, low-effort and low-cost approach for assessing the performance of rain gardens. Visual inspection criteria and infiltration rate measurement techniques were refined through numerous field tests performed over the course of a growing season. The results and the potential applications of these methods for the assessment of rain gardens will be discussed.

3. Levels of Assessment Overview

3.1. Visual Inspection (Level 1)

The visual inspection involves the evaluation of the vegetation and the soil of the rain garden. The conditions of inlet and outlet structures as well as the overall appearance of the site also provide visual indications of its functionality. The level of effort involved with doing a comprehensive visual inspection is greater than simple observations and requires some knowledge of vegetation and soils. While simpler observations such as visiting a site 48 hours after a runoff event to check for standing water require less effort, they only provide general information to determine if the rain garden is functioning properly. All of the components of the visual inspection provide information on different aspects of the rain gardens' function.

The first component includes examination of the rain garden for obvious limitation in hydraulic functioning. Ponded water should be present for no more than 48 hours after a rain fall event (Minnesota Stormwater Steering Committee, 2005). A longer drainage period indicates that the hydraulic properties of the soil should be examined further. Sediment accumulation in the basin could reduce infiltration rates and limit the treatment capacity of the rain garden. Erosion and could cause stormwater to be directed away from the rain garden while clogged outlet structures could lead to local flooding problems. Clogged inlet structures may indicate stormwater short circuiting and reduced treatment efficiency.

The next component of a detailed visual inspection is the assessment of the vegetation. There are several considerations to make when conducting this assessment such as age of the rain garden, time of the growing season, species present and their growing requirements, and the condition of the site. Vegetation plays a critical role in stormwater treatment by rain gardens and overall plant health signifies proper function. The species present should be monitored over time using the original vegetation design plans and photographic records. For example, the presence of wetland plant species indicates the formation of hydric soils due to prolonged saturation or ponding (Richardson and Vepraskas, 2001). A decline in the diversity of plant species present, the health of the vegetation and/or the percent cover is an indication that the rain garden is not functioning appropriately. Photographs of each site should be taken for record keeping purposes.

The last component of the visual assessment of rain gardens includes the inspection of the soil properties. The infiltration characteristics of a rain garden soil are directly related to the hydraulic conductivity and the porosity of the soil, and these in turn are affected by the texture and the bulk density of the soil (Hillel, 1998). The textural class of a soil, although not a direct measure of soil porosity or permeability, allows for the estimation of both parameters (Erickson et al., 2007). Estimates of saturated hydraulic conductivity (K_{sat}) based on the U.S. Department of Agriculture (USDA) soil textural classes from various authors are given in Table 3.1. Soil color is an easy to measure parameter that provides an indirect measure of soil characteristics such as water drainage, aeration, and organic matter content (Foth, 1990). For example, soils that are gray in color or contain mottles (i.e. small areas of gray, red, yellow, brown, or black that differ in color from the bulk soil) are indicative of hydric soils (Richardson and Vepraskas 2001). The presence of hydric soils is evidence of prolonged water saturation, indicating that stormwater runoff is not infiltrating in an acceptable amount of time.

Table 3.1. K_{sat} classified by USDA soil textural classes (Rawls et al.,1998; Saxton and Rawls, 2005).

	(Saxton and Rawls 2005)		**(Rawls et al. 1998)**		**(Clapp and Hornberger 1978)**	
Soil Texture (USDA)	**K_{sat} (cm/s)**	**Porosity (m^3/m^3)**	**K_{sat} (cm/s)**	**Porosity (m^3/m^3)**	**K_{sat} (cm/s)**	**Porosity (m^3/m^3)**
Sand	0.00431 0.00317	0.48 0.46	0.00505 0.00254	0.44 0.39	0.00824 -	0.40 -
Loamy Sand	0.00253 0.00126	0.46 0.43	0.00342 0.00115	0.45 0.37	0.00405 -	0.44 -
Sandy Loam	0.00140 0.00063	0.45 0.42	0.00155 0.00036	0.47 0.37	0.00123 -	0.44 -
Loam	0.00023 0.00052	0.48 0.46	0.00011 0.00017	0.47 0.39	0.00028 -	0.45 -
Silt Loam	0.00034 0.00180	0.48 0.46	0.00040 0.00009	0.49 0.39	0.00007 -	0.49 -
Silt	0.00053	0.48	-	-	-	-
Sandy Clay Loam	0.00011 0.00022	0.45 0.43	0.00021 0.00008	0.44 0.37	0.00025 -	0.42 -
Clay Loam	0.00013 0.00022	0.47 0.45	0.00012 0.00002	0.48 0.40	0.00007 -	0.48 -
Silty Clay Loam	0.00016 0.30000	0.51 0.49	0.00010 0.00014	0.50 0.43	0.00002 -	0.48 -
Sandy Clay	0.00002	0.44	0.00003	0.39	0.00003	0.43
Silty Clay	0.00011	0.53	0.00005	0.53	0.00001	0.49
Clay	0.00002 0.00005	0.49 0.46	0.00006 0.00005	0.48 0.40	0.00006 -	0.48 -

3.2. Capacity Tests (Level 2)

The primary function of rain gardens is to reduce runoff volume through infiltration. Therefore the capacity of the rain garden to infiltrate water is an important assessment parameter. Rain gardens are typically designed to drain within 48 hours or less after a runoff event because most plants used in rain gardens are not adapted to flooding and cannot survive submergence for longer periods of time (Shaw and Schmidt, 2003).

Several field devices have been evaluated for measuring K_{sat} (Dorsey et al., 1990; Johnson, 2006; Munoz-Carpena et al., 2002; and Reynolds et al., 2000). The applicability of these various devices for measuring the K_{sat} of rain garden and other stormwater BMP soils was further evaluated by Nestingen (2007) and included: the double ring infiltrometer (Klute, 1986), Guelph permeameter (Soilmoisture Equipment Corp., 1991), Minidisk infiltrometer (Decagon Devices, 2005), tension infiltrometer (Reynolds and Elrick, 1991) and a Modified Philip-Dunne infiltrometer (Nestingen, 2007). Table 3.2 compares each device based on several usability criteria.

The Phillip-Dunne permeameter, intended to be used in a borehole (Munoz-Carpena et al., 2002), was modified to incorporate the potentially limiting layer of surface soil and sediment (Nestingen, 2007). Due to the minimal volume of water necessary, ease of use in the field, low cost of the device, and transportability of the equipment, the Modified Philip-Dunne infiltrometer was selected for measuring the K_{sat} of the rain garden soils.

Table 3.2. Comparison of devices to measure saturated hydraulic conductivity of infiltration practices.

CRITERIA	Double Ring Infiltrometer	Modified Philip-Dunne Infiltrometer	Minidisk Infiltrometer	Guelph Permeameter	Tension Infiltrometer
Transportability of equipment	2	1	1	2	3
Volume of water needed	3	1	1	2	3
Experiment duration	3	2	1	3	2
Simplicity of operation	2	1	2	3	3
Cost	2	1	1	3	3
Personnel requirements	1	1	1	2	2
Accuracy	1	1	2	1*	2*

Criteria evaluation: 1 = most desired, 2 = second-most desired, 3 = least desired
* Device accuracy evaluation based on reports in the literature.

3.3. Synthetic Runoff Tests (Level 3)

The ultimate question during the assessment of a rain garden is whether it is draining within the required timeframe. While making use of natural runoff events to determine if the rain garden is draining within the required time frame may be possible, timing of the rain event may not be convenient. In addition, the volume of runoff produced by a typically rainfall event will not fill the basin to its capacity. Therefore having the ability to control the timing as well as the volume of water to determine the drain time is desirable. Synthetic runoff tests involve the use of a fire hydrant or water truck to fill the basin to capacity and measuring the time required for the water to drain. This level of assessment also allows for the opportunity to add pollutants of interests to the water to determine the pollutant removal efficiency of the rain garden. The synthetic runoff test provides a quick, easy and cost effective way to determine the time required for the complete drainage of a rain garden.

4. Methods

Twelve rain gardens throughout Minnesota were evaluated using the first three levels of assessment. Based on the first level of assessment four rain gardens were considered to be not functioning properly and further evaluation was not conducted. Of the eights rain gardens chosen for additional assessment three of the rain gardens included underdrains. The age of the sites varied from recently planted to five years.

4.1. Visual Inspection (Level 1)

The visual inspection provides qualitative information to evaluate whether the rain garden is functioning properly and includes: (1) hydraulic issues, (2) vegetation, and (3) soil. Based on these criteria a site may be selected for a more detailed assessment (i.e. level 2 or higher) or considered to be failing and in need of maintenance.

A visual assessment of the presence and health of the plants was made by examining and recording the color, size, and quality of the leaves, stem and flowers using the design plans when available along with a plant field guide to identify species. The percent cover that the vegetation provides was also estimated to ensure plants were growing adequately. The sites were also inspected for the presence of wetland plant species.

Soil texture was determined using the feel method (Wheeler and Wittwer, Undated) and the USDA Textural Triangle. The color of the soil was determined by matching the color of a soil sample from each layer with a color chip in a Munsell ® soil-color book. The visual inspection assessment results (functioning vs. nonfunctioning) were also used as part of the site selection process for determining whether a level 2 assessment would be necessary.

4.2. Capacity Tests (Level 2)

The Modified Philip-Dunne (MPD) infiltrometer (Figure 4.1) is an open-ended, thin-walled aluminum cylinder which has a maximum height of approximately 60 cm, a minimum height of 30 cm, and a diameter of 10 cm. A transparent piezometer tube is located 5 cm from the bottom on the outside of the device with measurement markings along it for making visual readings. Its use involves a falling head technique that assumes three-dimensional flow through isotropic homogeneous soil. The device was pounded into the soil to a depth of 5 cm then filled with water to a height of 43 cm. The water height over time was then recorded. Tests in which the water level failed to decrease within three hours were abandoned and assigned a K_{sat} value of zero.

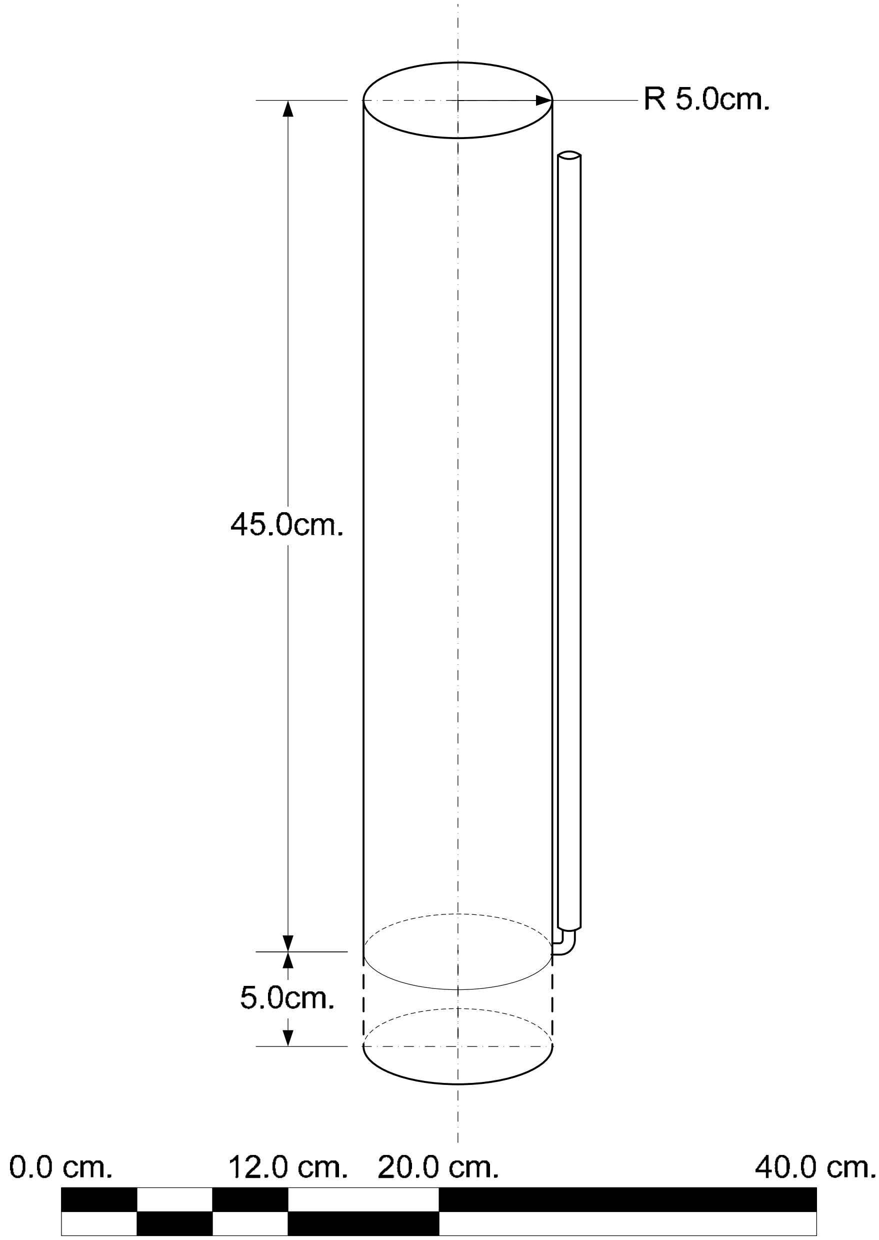

Figure 4.1. Diagram of the Modified Philip-Dunne infiltrometer.

A capacitance probe (Theta Probe ®, ML2x), which measures the dielectric constant of the soil, was used to indirectly measure the initial and final soil moisture content of the top 6 cm of soil. A soil specific calibration using several gravimetric soil moisture measurements was conducted for each rain garden. Bulk density measurements which were required to convert gravimetric water content to volumetric water content were made using the core method (Klute, 1986). The bulk density measurements were also used as an index of the degree of compaction. MPD infiltrometer measurements were made throughout each basin and the coordinates were determined using a Trimble ProXR GPS unit.

4.3. Synthetic Runoff Tests (Level 3)

The third level of assessment included filling the rain garden to capacity using a fire hydrant or water truck to evaluate the drain time of the entire rain garden. It was predetermined that at least three of the rain gardens being assessed would be chosen for a level 3 assessment. These rain gardens were chosen based on their relatively small size, access to fire hydrants or easy access to the rain garden using a water truck. Rain gardens where adequate flow was available to perform the synthetic runoff test were filled through curb cuts or storm sewer inlet structures, while taking care to dissipate the hydraulic energy. Two of the three sites where simulated runoff tests were conducted had fire hydrants nearby as well as trained assistants and the equipment necessary for connecting to and using the hydrant. The third site was filled using a water truck.

Once the rain gardens were filled with water the relationship of water level versus time was recorded using a staff gauge and a stop watch. Continuous measurements were collected every second and averaged over 10 second intervals with an ultrasonic sensor (MassaSonic, M-5000) mounted to a post at the lowest point in the basin.

5. Data Analysis

5.1. Capacity Tests (Level 2)

Five parameters were used to calculate the K_{sat} of the soil; the radius of the tube, the change in volumetric moisture content, the initial height of water in the tube, the time to the midpoint height, and the time to empty.

The results were input into ArcView to provide a map of the spatial variability K_{sat} for each rain garden. The median was then calculated for each site to describe the K_{sat} for the entire rain garden. The mean value was used to estimate the total time required for the rain garden to empty when filled to its capacity or water quality volume (WQV) for sites where a synthetic runoff test was conducted. First the infiltration discharge (Q_i) is calculated based on the measured median K_{sat} value and the surface area of the rain garden (A) (Equation 1). The time to drain is then determined using Equation 2. This time is then converted to hours to determine if the rain garden is draining within the required or desired timeframe.

$$Q_i = K_{sat} \times A \tag{1}$$

$$DrainTime = \frac{Q_i}{WQV} \tag{2}$$

5.2. Synthetic Runoff Tests (Level 3)

To determine if an adequate supply of water was available the required flow rate was calculated. The parameters necessary to estimate the flow rate required to flood the site include the surface area of the basin, the estimated or measured infiltration rate, and the storage capacity or WQV (m^3). Equations 3 and 4 give the relationships to compute the infiltration discharge and required flow rate, respectively (Erickson et al., 2007).

$$Q_i = Ai \tag{3}$$

$$Q = \frac{Q_i \Delta t + WQV}{\Delta t} \tag{4}$$

where Q_i (m^3/hr) is the infiltration discharge, A (m^2) is the average surface area of the basin, i (m/hr) is the estimated infiltration rate, Q (m^3/hr) is the required flow rate, and Δt (hrs) is the time to fill the basin.

During the synthetic runoff test the total time required for the entire basin to drain was measured. The result of this test was then compared to the drain time the rain garden was designed to achieve as well as the estimated drain times computed using the results of the MPD tests.

6. Site Selection and Descriptions

A total of twelve sites were evaluated to be included in the development and implementation of the four level assessment procedure. An initial visual inspection which consisted of inspection for ponded water along with rainfall records, inspection of the vegetation, determination of the soil texture and color, and observations of water content. The rain gardens which were determined to not be functioning properly were labeled A, B, C, and D. The evidence indicating inadequate functionality at these four rain gardens is now described. In addition to the visual inspection conducted as part of the assessment research, initial site visits were made the prior summer and all of the rain gardens discussed below contained ponded water and little vegetation.

There was ponded water at rain garden A (approximately 45 m^2 in size) and the last rainfall event of 0.05 cm had occurred 24 hours prior. While this may still have drained in less than 48 hours examination of the soil profile indicated that there was poor drainage occurring. Rain garden A contained underdrains which did not appear to be providing an additional drainage. There was a thin layer of a black mucky soil covering the entire basin. In addition a restrictive layer of a silty clay loam was found below the topsoil (silt loam). However, the vegetation in the rain garden was dense and appeared to be healthy. The soil conditions and the ponded water indicated that rain garden A was not draining properly. There was also the presence of a significant amount of sediment, grass clippings and leaves which was mucky with green moss growing on the surface accumulating at the curb cut inlet. Rain garden B (approximately 50 m^2 in size) had very little healthy vegetation and the topsoil was gray in color which indicated that gleying was occurring in the soils and that there was hydric conditions. Since hydric soils were found in rain garden B it was categorized as non-functional. Hydric soils and wetland vegetation were both found in rain garden C (approximately 140 m^2 in size), indicating its failure to act as a properly functioning rain garden. Rain garden D (approximately 180 m^2 in size) was determined not be functioning properly by the presence several species of emergent plants (i.e. adapted to living in standing water). The soils were not inspected at rain garden D based on the identification of wetland vegetation present and the ponded conditions with no runoff events occurring within a 48 hour period which was observed the prior summer. Based on the visual inspections conducted at these four rain gardens no further assessment was conducted due to their non-functionality.

Of the twelve rain gardens considered for use in the development of the assessment techniques, extensive data was collected at eight over one growing season. Table 6.1 is a summary of these rain gardens and the levels of assessment used. The sizes of the rain gardens ranged from 300 square feet to 14,500 square feet. The smallest rain garden was located in a residential area receiving stormwater runoff from the street via a curb cut inlet. Several other rain gardens received runoff from parking lot areas, or a combination of stormwater runoff sources. The three oldest rain gardens were installed in the fall of 2003 and were online (i.e., receiving runoff) in the spring of 2004. The

Ramsey Washington Metro Watershed District (RWMWD) office has a total of seven rain gardens located on site which were constructed in the spring of 2006. All seven of the rain gardens were designed with different types of vegetation and various levels of diversity. Rain gardens #1 through #3 were planted with a high diversity mix of vegetation, #4 and #5 had a medium diversity and #6 and #7 had the lowest diversity with #7 planted with only turf grass. Three of those rain gardens were assessed (#1, #4, and #5) and they were all offline (i.e. not receiving runoff) at the time of assessment. The University of Minnesota (U of M) - St. Paul rain garden received stormwater runoff for approximately one year prior to assessment. Only one of the rain gardens had a pretreatment practice installed, the U of M - Duluth site. A sediment forbay was located at the inlet of the rain garden. This site also contained underdrains to compensate for the clay soils in the area.

Table 6.1. Summary of rain garden assessment sites. VI is visual inspection, CT is capacity tests and SRT is synthetic runoff tests.

Rain Garden	Size	Level of Assessment	Underdrains
Burnsville	27.87 m^2	VI & CT	No
Cottage Grove	70.00 m^2	VI, CT & SRT	No
RWMDW (1)	146.97 m^2	VI & CT	Yes
RWMDW (4)	29.08 m^2	VI & CT	No
RWMDW (5)	58.62 m^2	VI, CT & SRT	No
Thompson Lake	278.17 m^2	VI & CT	Yes
U of M - Duluth	1,347.09 m^2	VI & CT	Yes
U of M – St. Paul	66.52 m^2	VI, CT & SRT	No

All sites listed in Table 6.1 were evaluated using both level one (i.e. visual inspection) and level two (i.e. capacity testing) assessment techniques. Three of the sites were evaluated using synthetic runoff testing (i.e. level three). Selection of these sites was based on the size of the rain garden and availability of a water supply. None of the sites where a level three assessment was conducted were constructed with underdrains. Three of the rain gardens assessed using the first two levels of assessment did contain underdrains and were also the three largest rain gardens evaluated.

7. Results and Discussion

7.1. Visual Inspection (Level 1)

The specific type of vegetation planted at each rain garden varies based on the expected solar radiation, soils present, location within the rain garden and the specific design plans. An overview of the type of vegetation present and its general health condition is given in Table 7.1

All of the rain gardens contained various species of native perennial vegetation. Four of the sites contained new plantings, and based on their stage in development were considered to be in good health. With the exception of the four sites determined to be not functioning properly most other sites had well established vegetation that appeared to be healthy. The Cottage Grove site was rated as poor based on the presence of failing trees. Nevertheless, the prairie grasses and perennial plants appeared to be established and growing well. Further inspection of the soil properties at this particular location will provide insight into possible causes of the failing health of the trees.

A soil core was taken to a depth of approximately forty-seven inches and the texture and color of that profile was determined in the field. Several bulk density samples were taken at each functional site for the conversion of water content and for a quantification of the level of compaction. The results of the inspection of the soils at each rain garden are provided in Table 7.2.

Rain gardens typically have mulch covering the soil surface. Seven of the eight sites evaluated the surface cover consisted of wood mulch. The topsoil of several rain gardens consisted of a sandy loam soil. Examining the entire soil profile of the rain gardens is important for the detection of restrictive soil layers which will control the rate at which water moves through the soil profile. At the U of M - St. Paul campus rain garden, for example, a lower permeability silt loam soil layer was underlying the sandy loam topsoil. Two additional sites had underlying native soil of finer texture than the overlying topsoil. These rain gardens, however, were designed with underdrains to compensate for this situation. The soil profile at the Cottage Grove site consisted of forty inches of sand overlying gravel. The poor retention of water and nutrients by sand are a potential cause of the failing plants discovered during the inspection of the vegetation.

Table 7.1. Vegetation type and health of rain gardens tested.

Rain Garden	Sun Conditions	Type of Vegetation	Overall Health
A	Full Sun/Partial Shade	Large shrubs	Good
B	Full Sun	Medium shrubs, perennial flowers and grasses, and ornamental plants	Poor
Burnsville	Full Sun	Large to medium shrubs, perennial flowers and grasses, and ornamental plants	Good
C	Full Sun/Partial Shade	Medium shrubs, sedges, perennial flowers and grasses, and ornamental plants	Poor
Cottage Grove	Full Sun	Trees, perennial plants and grasses	Poor
D	Full Sun/Partial Shade	Cattails, arrowheads, marsh smartweed and some perennial flowers	Good
RWMWD (1)	Full Sun	Asters, sedges, perennial flowers and native grasses	Good (new plantings)
RWMWD (4)	Full Sun	Sedges and native grasses	Good (new plantings)
RWMWD (5)	Full Sun	Asters, sedges, perennial flowers and native grasses	Good (new plantings)
Thompson Lake	Full Sun	Large, medium and small shrubs, native plants, perennial flowers and grasses	Good
U of M - Duluth	Full Sun/Partial Shade	Asters, sedges, perennial flowers and native grasses	Good (new plantings)
U of M - St. Paul	Partial Shade	Perennial flowers and grasses and ornamental plants	Fair

The topsoil bulk density of each site is also listed in Table 7.2. The number of measurements taken varied at each site (Burnsville = 23, Cottage Grove = 8, RWMWD #1 = 7, RWMWD #4 = 2, RWMWD #5 = 8, Thompson Lake = 10, U of M - Duluth = 8, and U of M - St. Paul = 21) and the results were averaged for an overall bulk density of the rain garden. Two sets of samples were taken for the U of M - Duluth rain garden as it contained two different types of media. The bulk density of soils under standard conditions ranges from 1.3 to 1.35 g/cm^3. Sandy soils with a relatively low volume of pores may have a bulk density of 1.6 g/cm^3, whereas aggregated loams and clays soils may fall below 1.2 g/cm^3 (Hillel 1998). The bulk density of the coarse sand overlying the underdrain system at the U of M - Duluth rain garden was 1.526±0.266 g/cm^3. The measured bulk densities of the rain gardens assessed cover a wide range values, but fall within the expected ranges. Based on these measurements, compaction did not appear to be a problem for any of the rain gardens.

Table 7.2. Soil properties of rain gardens assessed with the capacity testing approach.

Rain Garden	Soil Cover	Soil Profile	Bulk Density (g/cm^3)
A	None	0-15.2 cm – Silt Loam, 10YR 3/2 15.2-22.9 cm – Silty Clay Loam, 10YR 4/4 22.9-119.4 cm – Sand, 10YR 4/4	NA
B	None	0-5.1 cm – Organic Matter, Gley 2.5/N 5.1-38.1 cm – Silt Loam, 10YR 3/2 w/ red mottles 38.1 cm – hard surface (unable to penetrate)	NA
Burnsville	Thick Wood Mulch	0-30.5 cm - Sandy Loam, 10YR 2/2 30.5-119.4 cm - Sand w/ large rocks, 10YR 3/4	1.128 ± 0.218
C	None	0-6.4 cm – Organic Matter, 5Y 2.5/1 6.4-17.8 cm – Sand, 10YR 4/3 17.8 – 28.0 cm Sandy Clay Loam, Gley 4/10Y w/ red mottles 28.0 – 119.4 cm Loamy Sand w/ large rocks, 5YR 4/3	NA
Cottage Grove	None	0-76.2 cm - Sand, 10YR 3/2 76.2-101.6 cm - Sand, 10YR 4/4 101.6-119.4 cm - Gravel	1.573± 0.076
D	None	NA	NA
RWMWD (1)	Wood Mulch	0-38.1 cm - Sandy Loam, 5YR 2.5/1 38.1-50.8 cm - Sandy Loam, 10YR 3/4 50.8-119.4 cm - Sand, 10YR 3/4	1.202± 0.084
RWMWD (4)	Wood Mulch	0-38.1 cm - Sandy Loam, 5YR 2.5/1 38.1-50.8 cm - Sandy Loam, 10YR 3/4 50.8-119.4 cm - Sand, 10YR 3/4	1.323± 0.068
RWMWD (5)	Wood Mulch	0-38.1 cm - Sandy Loam, 5YR 2.5/1 38.1-50.8 cm - Sandy Loam, 10YR 3/4 50.8-119.4 cm - Sand, 10YR 3/4	1.193± 0.163
Thompson Lake	Wood Mulch	0-12.7 cm - Loamy Sand, 10YR 2/2 12.7-43.2 cm - Sand w/ med. to large rocks, 10YR 5/4 43.2-119.4 cm - Silt Loam, 10YR 3/1	1.096± 0.175
U of M - Duluth	Wood Mulch	0-45.7 cm - Sandy Loam, 10YR 2/2 45.7-116.8 cm - Clay, 5YR 4/4 116.8-? cm - Clay w/ gray modeling, 5YR 4/4	0.947± 0.106
U of M - St. Paul	Wood Mulch	0-20.3 cm - Sandy Loam, 10YR 2/2 20.3-48.3 cm - Silt Loam, 10YR 2/1 48.3-119.4 cm – Sand (non-native), 10YR 6/4 119.4-? cm – Silt Loam w. coarse sand, 2.5YR 3/3	1.182± 0.127

[1]10YR 2/2 is the notation used to describe the hue, value and chroma of the soil color.
[2]Represents the soil of the rain garden, not the sand portions overlying the underdrain system.

7.2. Capacity Tests (Level 2)

The number of locations where measurements were made using the MPD varied at each rain garden. The general statistics of the measured K_{sat} values using the MPD infiltrometer are summarized in Table 7.3.

Table 7.3. Standard statistics for measured K_{sat} using the MPD at rain gardens.

Statistical parameter	Burnsville	Cottage Grove	RWMWD (1)	RWMWD (4)
No. of measurements	24	20	12	4
Mean (cm/s)	0.01777	0.02375	0.00748	0.00317
Median (cm/s)	0.01293	0.01958	0.00535	0.00401
Std. Dev. (cm/s)	0.01782	0.01364	0.00707	0.00214
CV (%)	100.2	57.4	94.6	67.4
Skewness	2.29	0.91	1.84	-1.84
Min. (cm/s)	0.00055	0.00403	0.00082	0.000009
Max. (cm/s)	0.08148	0.05358	0.02578	0.00467
Range (cm/s)	0.08093	0.04955	0.024962	0.00466
	RWMWD (5)	Thompson Lake	U of M - Duluth	U of M -St. Paul
No. of measurements	16	30	33	40
Mean (cm/s)	0.00329	0.01208	0.00906	0.00428
Median (cm/s)	0.00081	0.00531	0.00159	0.00288
Std. Dev. (cm/s)	0.00486	0.01484	0.01612	0.00375
CV (%)	147.5	122.8	177.9	87.7
Skewness	1.78	1.58	2.40	1.31
Min. (cm/s)	0.00018	0.0000007	< 0.0000007	< 0.0000007
Max. (cm/s)	0.01570	0.05405	0.06363	0.01515
Range (cm/s)	0.01552	0.05405	0.06363	0.01515

The distributions of the measured K_{sat} values were skewed for all the rain gardens. Therefore the median was used to describe the overall K_{sat} for the basin. The variability of K_{sat} was extremely large as expected (Hillel 1998) and the coefficient of variation (CV=Std. Dev./Mean) ranged from 57% to 174% (see Table 7.3). The estimated K_{sat} values which would be necessary to achieve a 48 hour drainage period were calculated using the dimensions of the rain garden at sites where a synthetic runoff test was conducted and compared to the mean value obtained from the MPD tests (Table 7.4).

Typically as the WQV of the rain garden decreases, so does the observed K_{sat} for a 48 hour drain time.

Table 7.4. Expected K_{sat} values for a 48 hour drain time compared to the median values measured with the MPD.

	48 hour K_{sat} value (cm/s)	**Measured K_{sat} (cm/s)**
Cottage Grove	0.00012	0.0196
RWMWD #5	0.00006	0.0054
U of M, St. Paul	0.00003	0.0029

The Burnsville rain garden (Figure 7.1) contained the highest measured K_{sat} value and the median for the entire basin was the second highest of the eight sites. The presence of large to medium sized rocks and dense shrubs along the west edge of the basin it was problematic for MPD testing. The thick mulch layer posed problems for the calibration of the soil moisture capacitance probe as some of the mulch was mixed into the soil. The large quantity of mulch and the presence of rocks below the soil surface affected the bulk density measurements and subsequently the soil moisture measurements. To compensate for this bulk density measurements were taken from each location where a MPD test was performed (with the exception of one sample which was spilled). Despite attempts to accurately calibrate the capacitance probe the resulting correlation coefficient was low at this site. The MPD infiltrometer tests were finished within 10 minutes at 39% of the locations allowing for very few water level measurements to be recorded at those locations. For these tests, the three data points (water level versus time) that were collected were plotted and an exponential fit was used to obtain additional data points via interpolation for subsequent calculation of K_{sat}. The highest measured K_{sat} values ($\geq 3.3 \times 10^{-2}$ cm/s) were typically near the shrubs and grasses; the lowest K_{sat} value (5.5×10^{-4} cm/s) was near the inlet while the other low values (6.2×10^{-3} cm/s) were randomly located throughout the basin.

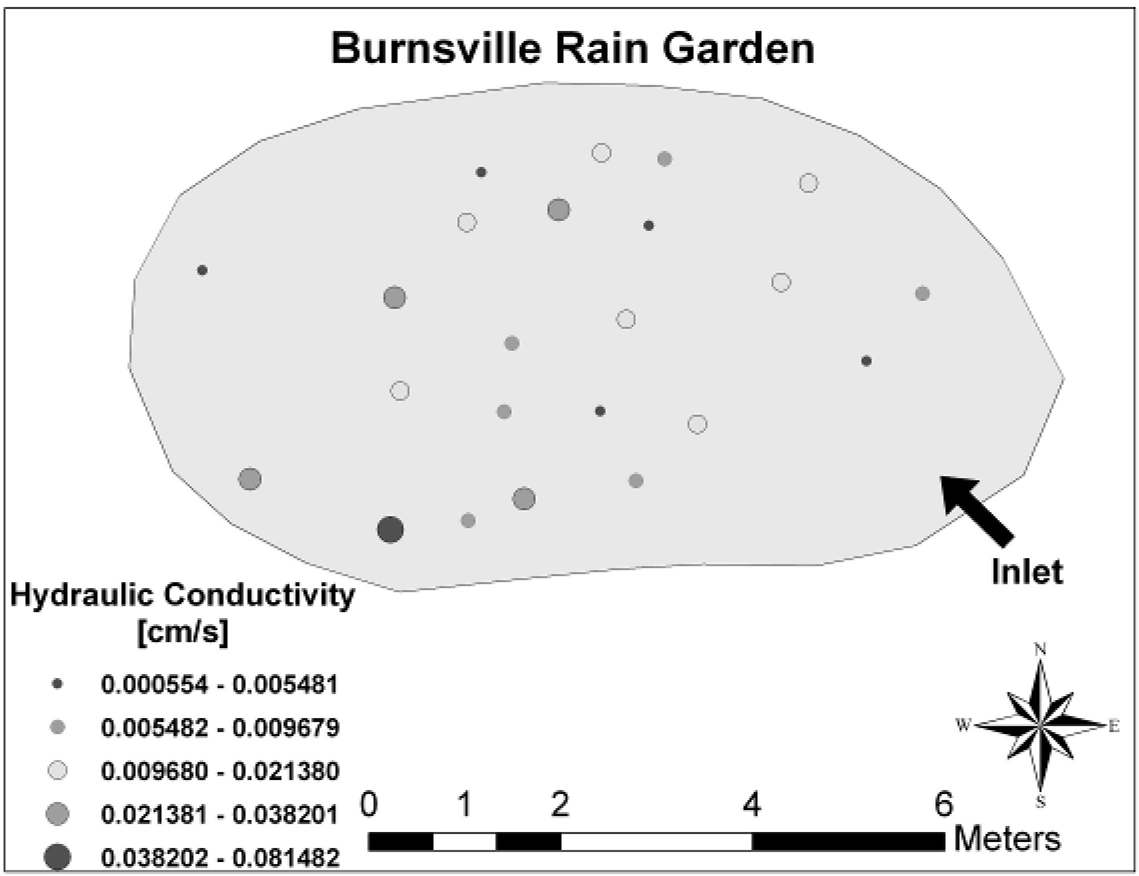

Figure 7.1. Measured K_{sat} values at the Burnsville rain garden.

The Cottage Grove rain garden (Figure 7.2) contained sandy soils which likely contributed to the closest to normal distribution of K_{sat} among the sites which is indicated by the low CV value (57.4%) and low skewness value (0.91). The sandy soils allowed for rapid infiltration resulting in 65% of the MPD infiltrometer tests finishing within 10 minutes and therefore requiring the interpolation of data points. The higher K_{sat} values ($\geq 2.2 \times 10^{-2}$ cm/s) were located near the failing trees, along the sideslopes of the rain garden. While the trees may have not been alive, the root systems were likely still providing preferential flow paths for the water.

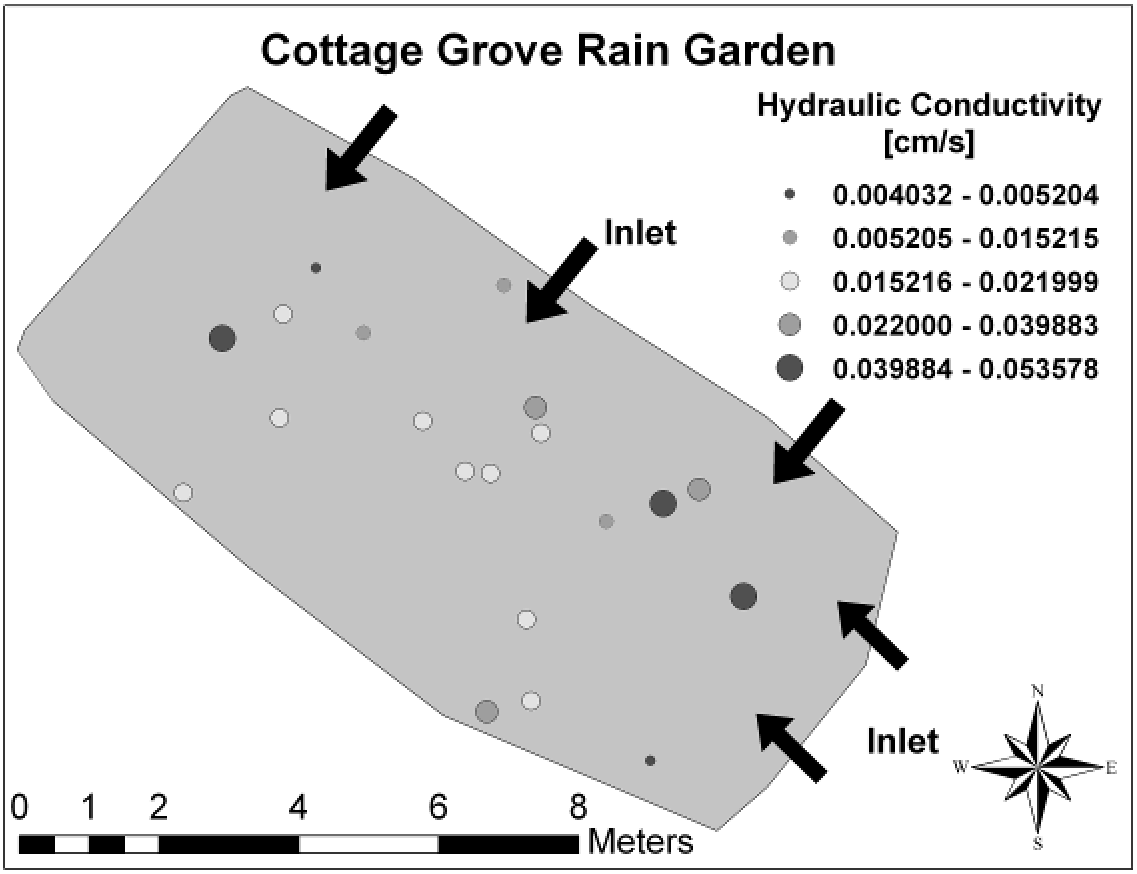

Figure 7.2. Measured K_{sat} values at the Cottage Grove rain garden**.**

The three rain gardens assessed at the RWMWD office were combined into one map (Figure 7.3). Rain garden #2 is the north western portion of rain garden #1, which is shown on the map with no locations of MPD tests. Rain garden #3 is the smallest of the seven located on site and is located directly above rain garden #2. Rain garden #1 is the largest of the three and had the highest variability in measured K_{sat} of the three (range = 0.024962 cm/s). It is the only basin containing underdrains which were closed at the time of assessment. Rain garden #1 receives stormwater from several sources including all of the runoff from the roof of the building. Rain garden #4 receives runoff from the street and overflows into rain garden #1. Only four measurements were made in rain garden #4 due to its small size. Rain garden #5 had the highest median of the three sites, with the lowest K_{sat} values concentrated near the inlet on the south east corner. While all of the rain gardens were offline (i.e. not receiving runoff) at the time of assessment, signs of sediment accumulation near the inlet and around the sandbags of rain gardens #4 and #5 were observed. The source of the sediment may have been the sandbags themselves. Compaction could have also occurred near the inlets during construction of the rain gardens.

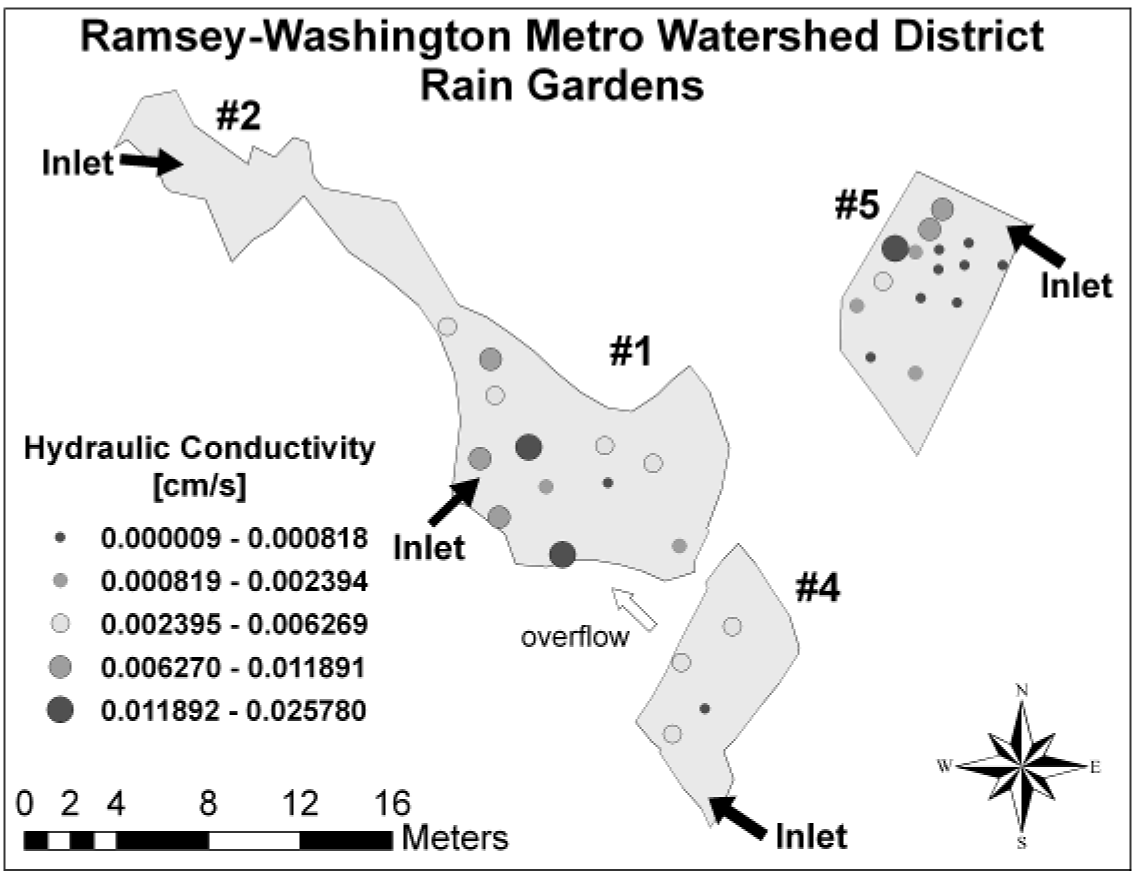

Figure 7.3. Measured K_{sat} values at the RWMWD rain gardens.

The Thompson Lake (Figure 7.4) rain garden also contained underdrains; however their location was unknown at the time of assessment. There were two relatively small curb cut inlets along the west portion of the rain garden receiving stormwater runoff from a parking lot. As one of the oldest rain gardens assessed the vegetation was more dense and larger than at the other sites. The highest K_{sat} values appear to coincide with the locations of large shrubs. The large and dense cover of vegetation likely contributed to the higher K_{sat} values measured at this site resulting in the third highest median K_{sat} (0.00531 cm/s).

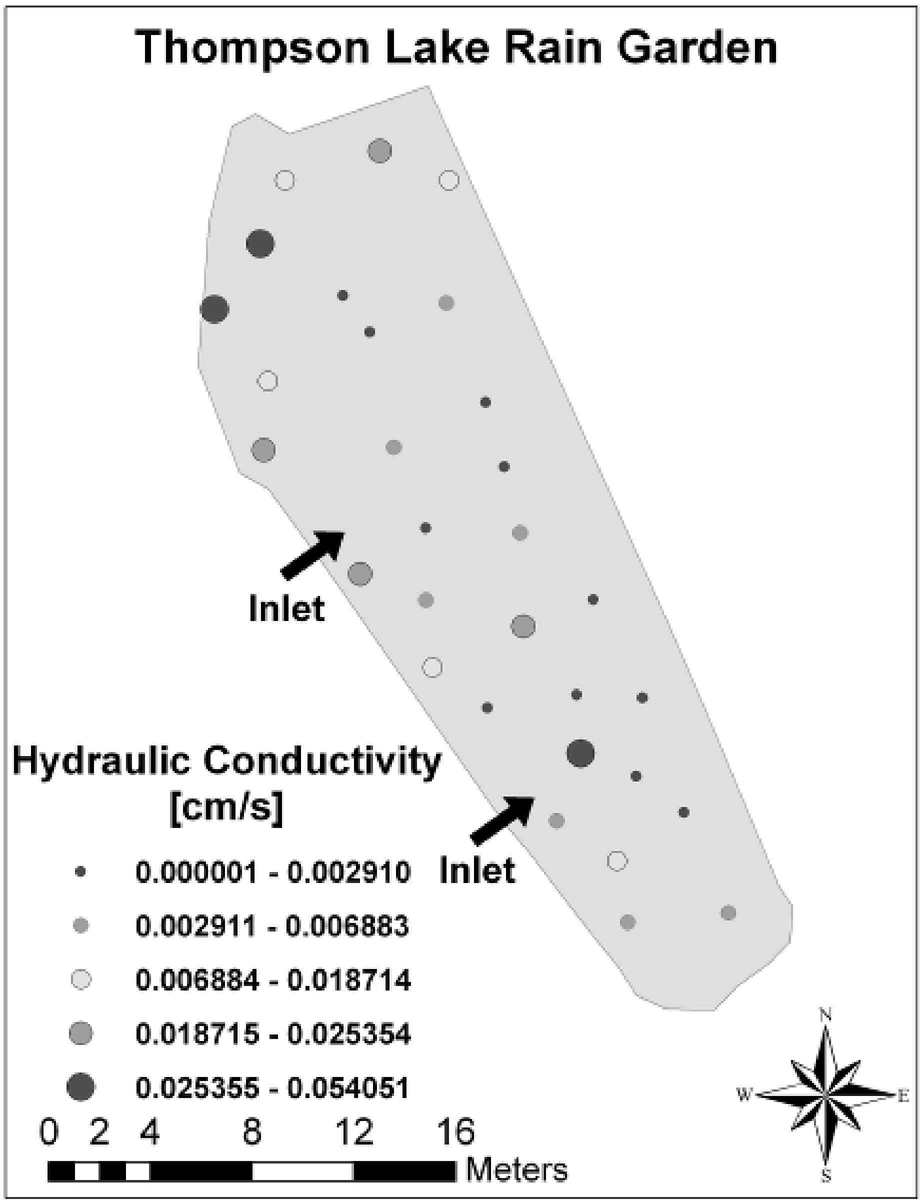

Figure 7.4. Measured K_{sat} values at the Thompson Lake rain garden**.**

The rain garden with the highest CV (177.9%) was the one at the U of M - Duluth campus (Figure 7.5) and is likely a result of the presence of two distinct types of media. A very coarse sand was located directly over an underdrain system while the vegetative portions of the rain garden contained a sandy loam overlying clay. The overall size of this rain garden 1,347.09 m^2 which consisted of both upland or woodland zones and "wetland" zones (actual rain garden). The areas shown in Figure 6 which do not have the locations of MPD tests are the woodland areas which do not participate in the infiltration of stormwater runoff. The lines within the perimeter of the entire site indicate the separation of these two distinct zones. The two areas located at the southeast corner of the overall site were called ornamental zones which would participate in the infiltration of stormwater runoff during large rainfall events. Since these areas do not receive runoff as often as other portions of the rain garden, only 18% of the total MPD tests were conducted in those zones. Measurements were concentrated near the inlet ("wetland" zone) of the rain garden and a few were made along the pathways of the underdrains (coarse sand portion). The highest measured K_{sat} values were primarily located on the course sand directly over the underdrains. The existing clay soils found at this site required the use of underdrains for proper drainage. As stormwater enters the rain garden via the sediment forbay it likely flows directly to the areas containing the coarse sand and is then flows downward into the tile drains. It is uncertain whether or not the coarse sand provides any treatment of the runoff as typically finer sands are used for filtration processes. This creates a unique situation where two different medias are utilized within the same basin; infiltration through the soil media and percolation through the coarse sand. The low K_{sat} values (< $2.6x10^{-3}$ cm/s) were primarily in the vicinity of the sediment forbay (northwest corner) and riprap inlet (southwest corner) of the rain garden.

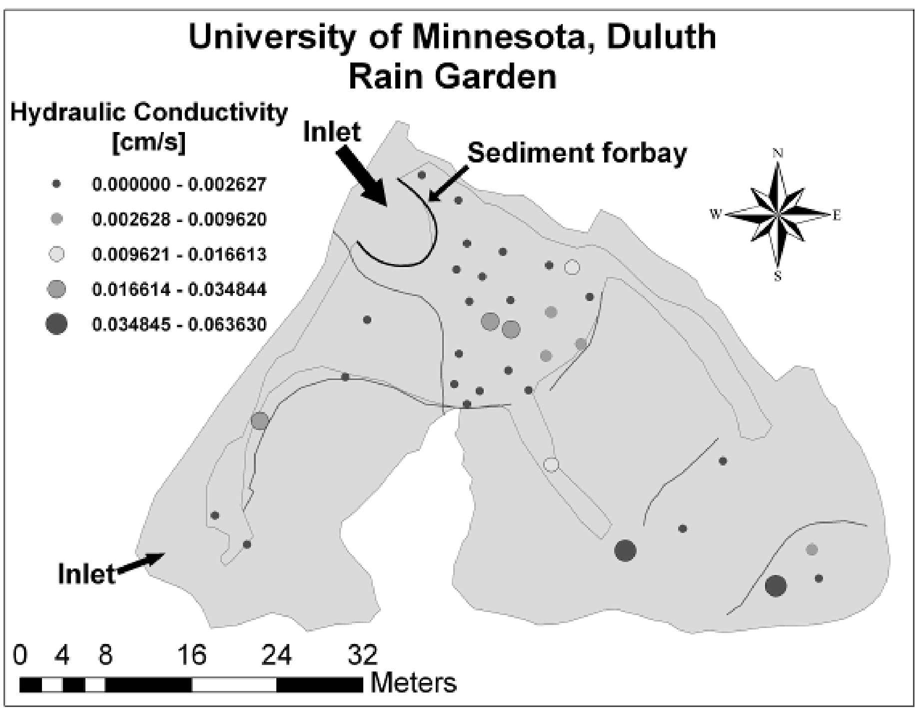

Figure 7.5. Measured K_{sat} values at the U of M - Duluth rain garden.

At the U of M - St. Paul campus rain garden (Figure 7.6), all of the low K_{sat} values (< $2.9x10^{-3}$ cm/s) were located near the center of the basin. Two of the MPD tests conducted in the center of the basin required more than 4 hours to drain. Overall 70% of the MPD tests were completed in less then 45 minutes. The low K_{sat} values found here could be a combination of the restrictive soil layer found at the 20 to 48 cm depth and the settling of particles from the stormwater runoff. This rain garden receives stormwater from both the storm sewer system and from the street via a curb cut. The inlets occur at the north and northwest portion of the rain garden, which is also where one MPD test was considered to result in a K_{sat} value of < 0.0000007 due to no change in the water level over a time period of several hours

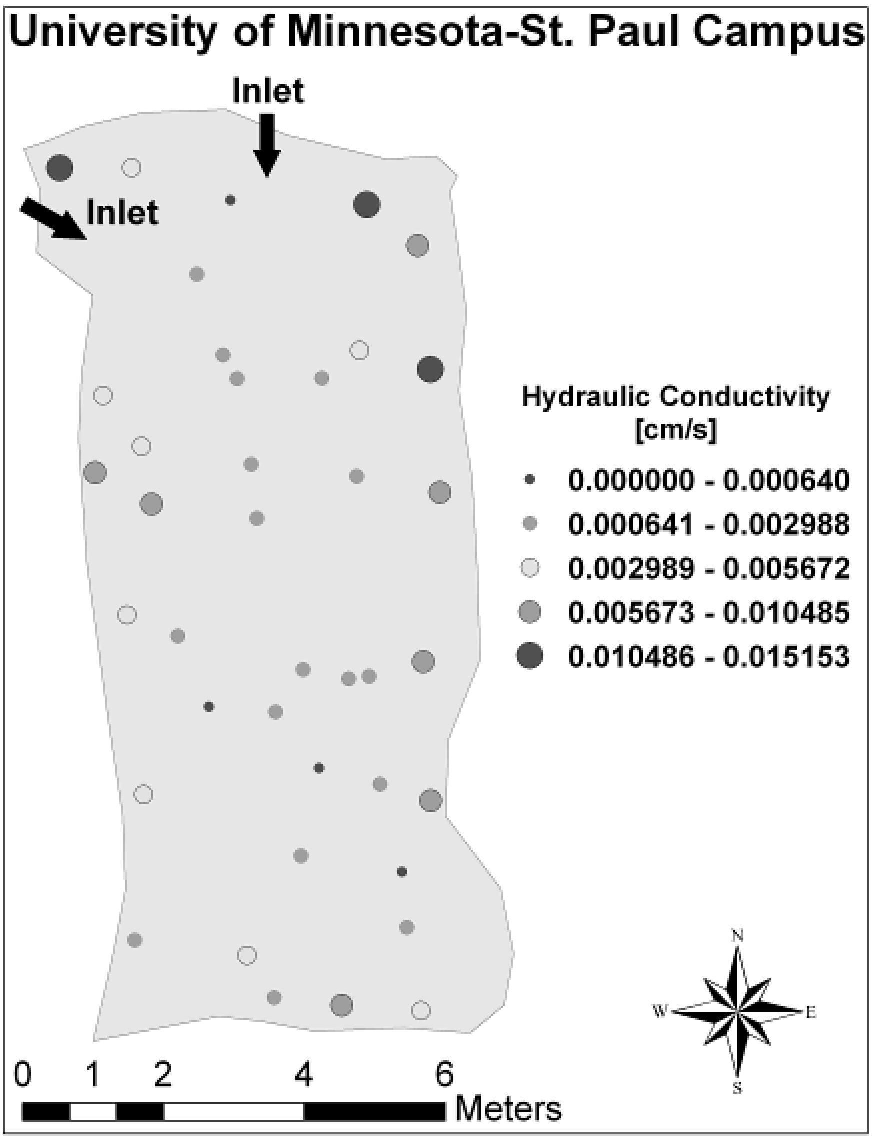

Figure 7.6. Measured K_{sat} values at the U of M - St. Paul rain garden**.**

In summary the lowest K_{sat} values occur most often near inlets and at the center of the basins, coinciding with the areas most impacted by water flow and sedimentation. All of the measured K_{sat} values resulted in a skewed distribution, which a lognormal transformation was found to provide the closest to normal distribution. The distribution of all six rain gardens is shown in Figure 7.7. The K_{sat} data from the three RWMWD rain gardens were combined for this comparison. The U of M - Duluth rain garden contained some of the lowest (< $6.0x10^{-7}$ cm/s) and highest (> $5.0x10^{-2}$ cm/s) K_{sat} values giving it the widest distribution of all the rain gardens. The smallest distribution was observed at the Cottage Grove rain garden where all of the measured K_{sat} values ranged between $4.0x10^{-3}$ cm/s and $5.4x10^{-2}$ cm/s. With the exception of the Cottage Grove rain garden, there were several locations having a K_{sat} value less than $5.5x10^{-4}$ cm/s. Two of the rain gardens, U of M - Duluth and U of M - St. Paul, contained one assumed K_{sat} value < $6.0x10^{-7}$ cm/s based on the observation of no decrease in water level over a period of 2 hours or longer and the lowest measured value. While the lowest K_{sat} values are of concern, the majority (82%) of the total MPD tests resulted in K_{sat} values greater than $1.0x10^{-3}$ cm/s. The soil properties and size and/or type of vegetation present in each rain garden appeared to influence the location of both the highest and lowest measured K_{sat} values which corresponds to the information in the literature regarding the spatial variability of K_{sat} (see appendix A for literature review).

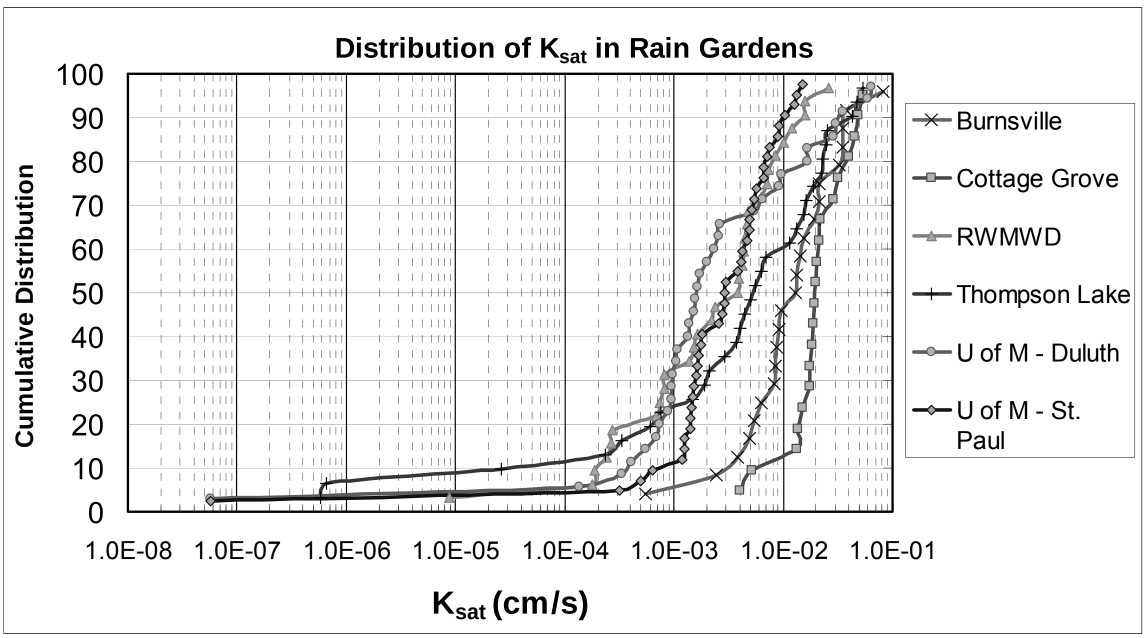

Figure 7.7. Distribution of MPD measured K_{sat} for all eight rain gardens.

7.3. Synthetic Runoff Tests (Level 3)

The rain gardens selected for synthetic runoff testing were Cottage Grove, RWMWD #5, and the U of M - St. Paul campus (Table 6.1). Synthetic runoff tests were not performed on same days that the capacity testing was conducted. A fire hydrant was used to fill both the RWMWD #5 and U of M - St. Paul rain gardens. The Cottage Grove rain garden required the use of a water truck filled with 15.14 m^3 of water. The U of M - St. Paul rain garden was the only site filled to capacity during the synthetic runoff test (Table 7.5). This site had an overflow weir connected to a second rain garden. The rain garden was filled until water began to overflow into the next rain garden and measurements began when overflow ceased. The use of a water truck to fill the Cottage Grove rain garden was fairly simple as it was located in a large parking lot with flat curbs along both the north and east sides. The Cottage Grove rain garden had a high infiltration rate and a fixed volume of water was available to fill the basin. Measurements began when the water truck was empty which resulted in a significant difference between the WQV and the volume utilized during the synthetic runoff test (Table 7.5). A fraction of the water applied to the Cottage Grove rain garden was lost as runoff due to the method of water delivery (used a dissipater with low flow to prevent erosion). The RWMWD #5 rain garden was filled as close to the maximum capacity as possible without overflowing the basin. The time required to fill the rain gardens was approximately 30 minutes. All of the rain gardens drained completely within 3 hours or less Figure 8.1.

Table 7.5. Water quality volumes (WQV) for rain gardens where SRTs were conducted.

	WQV(ft^3)	**SRT volume (ft^3)**
Cottage Grove	483.9	135.5
RWMWD #5	315.5	227.9
U of M - St. Paul	163.3	163.3

8. Summary

Based on the results of the visual inspection alone eight of the twelve rain gardens appeared to be functioning properly. The primary indicator of failure was the presence of hydric soils and/or wetland vegetation. While the health of the wetland vegetation as considered good, these plants are not desired for rain gardens. Other rain gardens which “passed” the visual inspection such as the Cottage Grove rain garden which contained failing trees and the sparse cover of vegetation near the inlet and the bottom of the basin of the U of M – St. Paul rain garden indicated the potential for problems. Also the presence of a limiting layer of soil below the surface at the U of M - St. Paul rain garden suggested that infiltration rates might be low. The results of the capacity tests and the synthetic runoff tests also indicated that the rain gardens were all draining within the required time frame and therefore functioning properly. Evaluating each rain garden using a multi-level assessment approach allows for a more detailed understanding of rain garden performance. A summary of the results for the vegetation inspection, soils inspection, and capacity testing conducted at each rain garden is provided in Table 8. The Cottage Grove rain garden provides an example of the importance of evaluating all components of the rain garden to understand its performance. The sandy soil observed during examination of the soil profile suggested that the Cottage Grove rain garden would have difficulty supporting vegetation but should have high infiltration rates. The soil profile results also shed light on potential drainage issues. As seen in Table 8.1, three of the rain gardens contain a restrictive soil layer below the surface soil. The restrictive layer will control the infiltration rate of the entire basin which will influence the drain time during large storm events if there are no underdrains in the rain garden. This is what we believe occurred at the U of M - St. Paul campus rain garden. The results of the assessment conducted at both the Cottage Grove and U of M - St. Paul rain gardens exemplify the role that vegetation and soils play in determining the rain gardens level of performance. The visual inspection does not require extensive time or effort and results in beneficial information to determine the relative efficiency of rain gardens.

The data collected in the level 2 assessment not only provided information about the spatial variability of K_{sat}, but also allowed for the estimation of the time required for the rain garden to drain. The arithmetic mean value of K_{sat} obtained from the MPD tests was used to estimate the drain time based on the same water quality volume used for each synthetic runoff tests (Figure 8.1). Drain time estimates based on the mean value of the MPD tests for all three rain gardens were overestimated compared to the synthetic runoff test. The difference between the estimated and measured drain time may be due to the higher concentration of low K_{sat} locations near the center of the rain gardens, which would retard the completion of a synthetic runoff test. In addition, no MPD measurements were taken directly over plants. Finally, the drain time of the U of M - St. Paul rain garden reflected an influence of the restrictive soil layer on drainage when the rain garden is filled to capacity, which may not have been detected using the MPD. In the point measurements made with the MPD infiltrometer, the limiting soil layer would not be a factor because of the small volume of water used in these tests and the ability for the water to flow laterally. Conducting a synthetic runoff test without level one and two assessments would not have indicated any problems with the U of M - St. Paul rain garden as it drained within the required time. Therefore the potential influence of steam flow on the infiltration rate when the rain garden is ponded would only be observed during SRTs.

Table 8.1. Comparison of visual inspection and capacity testing results.

Rain Garden	Overall Plant Health	Soil Profile	Median K_{sat} (cm/s)
Burnsville	Good	Sandy Loam Sand w/ large rocks	0.01293
Cottage Grove	Poor	Sand Sand Gravel	0.01958
RWMWD (1)	Good (new plantings)	Sandy Loam Sandy Loam Sand	0.00081
RWMWD (4)	Good (new plantings)	Sandy Loam Sandy Loam Sand	0.00401
RWMWD (5)	Good (new plantings)	Sandy Loam Sandy Loam Sand	0.00535
Thompson Lake	Good	Loamy Sand Sand w/ med. to large rocks Silt Loam	0.00531
U of M - Duluth	Good (new plantings)	Sandy Loam Clay Clay w/ gray modeling	0.00163
U of M - St. Paul	Fair	Sandy Loam Silt Loam Sand (non-native) Silt Loam w. coarse sand	0.00293

The cost and relative effort involved in the level 2 and 3 assessments are minimal in comparison to monitoring. These methods also allow for a more controlled environment and allows for predetermined timeframe for assessment. The benefit to conducting a level three assessment is that the drain time can be determined quickly and accurately. There is also the potential to incorporate pollutants of interest into the synthetic stormwater for determining pollutant removal efficiencies. However, the use of public water supplies for testing does require communication with city workers for permission and assistance. There are also locations where the required discharge to fill a given rain garden is unavailable.

While the first three levels of assessment are in most circumstances desired over monitoring, each level itself provides information not available by the others. For example while determining the soil texture allows for the determination of the presence of restrictive layers below the surface and can be used to estimate infiltration rates, the actual K_{sat} of the soil is not known. The capacity testing provides measured values of K_{sat} and how it varies spatially throughout the basin. This information is useful for identifying specific locations where maintenance is needed which saves money and may prolong the life of the rain garden. The determination of the effect that specific plants have on infiltration can be evaluated with use of the capacity testing data. The level 2 assessment also provides the opportunity to ensure that the construction of the rain garden was done properly and allows for the identification of locations which may have been compacted during construction. While capacity testing has numerous benefits it is limited in that the amount of time required for the rain garden to drain when full can only be estimated. The synthetic runoff test provides the solution to measuring the precise drainage time quickly and with little cost and effort.

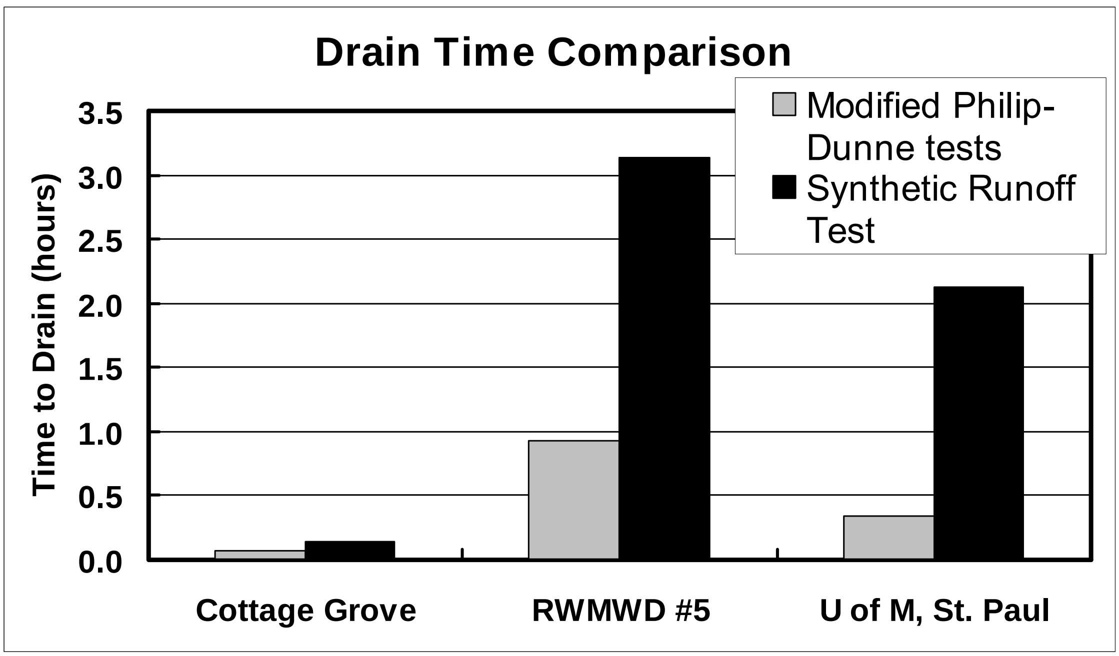

Figure 8.1. Comparison of measured drain times obtained from synthetic runoff tests (SRT) with drain times estimated using the median values from Modified Philip-Dunne (MPD) infiltrometer tests.

9. Conclusion

The methods described in this paper are useful tools for assessing the performance of rain gardens and other infiltration BMPs. All three levels of assessment provided helpful information regarding the overall function of rain gardens. Visual inspection of the vegetation and soils provided information on their ability to contribute to the uptake and infiltration of stormwater runoff adequately. Capacity testing provided information on the spatial variability in K_{sat} which could be used to estimate the overall drain time of the rain garden. The combination of level one and level two assessments is particularly useful for assisting in the development of maintenance tasks and schedules. Synthetic runoff tests (level 3) are a quick and easy method to most accurately determine drain times and can be used to assess the removal efficiencies of particular pollutants. Of the twelve rain gardens assessed in this research, four were not functioning properly and two of them had the potential for failure. The multi-level assessment approach allowed for the identification of potential causes and therefore solutions to solving the problem. The development and application of this assessment approach demonstrated that assessment using all three levels is the most effective and comprehensive method for evaluating the ability of rain gardens to treat stormwater. Nevertheless, when there are a large number of rain gardens to evaluate and limited funds available, periodic level 1 assessment can be used to identify obvious problems.

10. Future Research Needs

While the use of rain gardens to treat stormwater runoff is a common stormwater BMP practice in urban and suburban areas, there is still much to learn regarding their long term function, maintenance requirements, and optimal performance requirements. The interactions occurring among the stormwater, soil and vegetation are numerous and complex. Quantifying these interactions and the implications that they may have is necessary as rain gardens implementation increases. The tools developed through this research provide an opportunity to use standardize techniques which can be compared among researchers for a comprehensive understanding of the performance of rain gardens under various conditions to treat stormwater runoff.

The type of vegetation planted in rain gardens varies by region, landscape architect, desired function, available budget, and aesthetics. While there are several factors to take into consideration when choosing vegetation for a rain garden, the function they provide should be the most important. Scientific research is needed to provide those designing and installing rain gardens with the information regarding the optimal vegetation for improved infiltration, pollutant removal, and sustainability. It is well documented that highly vegetative landscapes have highly macroporous soils and therefore increased infiltration via preferential flow paths. The specific plant types which have the potential to provide the highest increase in infiltration over time needs to be documented. In addition to the preferential flow paths that the root mass is known to provide, it has also been suggested the stem flow occurring directly over the base of the plant under ponded conditions may provide substantial infiltration of water. The amount of infiltration occurring due to stem flow for varies species of plants is another component of vegetations interaction in stormwater treatment. In addition to the improved infiltration rates that various species of plant may provide their uptake of nutrients is also documented as function provided by vegetation in rain gardens. Plants all have specific nutrient requirements, this information as well as the amount of nutrients entering the rain garden needs to be evaluated to understand the amount of nutrients which may remain in the soil. The long term concentration of nutrients, particularly nitrogen, remaining in the soil may have implications for nearby ground water. The role that specific plants play in the treatment of stormwater runoff needs to better understood and available for the design and installation of rain gardens.

There are several different recommendations for the appropriate mix of soil, compost and sand to use in rain gardens. The Minnesota Stormwater Manual, Version 1.0 (2005) uses the recommendation of the Prince George's County Bioretention Manual (2002) for a soil medium consisting of 50-60% sand, 20-30% top soil, and 20-30% leaf compost which overlies a high permeability soil (>1 in/hr). Others have suggested lesser percentages of top soil or perhaps no top soil at all. The top soil and compost is necessary for plant survival and the sorption of pollutants. The cation exchange capacity (CEC) of soil is a major mechanism for the sorption of pollutants due to the negative charge associated with clay particles and organic particles. The elevated concentration of pollutants present in the stormwater runoff which are received by the rain gardens may alter the natural CEC of the soil. Additional research is necessary to fully understand the magnitude of this altered CEC and a timeline for which the soil may loose its capacity to adsorb pollutants. The conditions under which microorganisms that aid in biochemical transformations and the overall health of the soil can survive is another component which should be taken into consideration. The optimal composition of the soil medium for the maximum treatment of pollutants is a design decision that should be made with the assistance of scientific research results.

The long term performance and maintenance requirements are other areas which have received little research. This may be partly due to the fact that the design and implementation of rain gardens as a stormwater BMP is a relatively new practice. Research studies that explore how rain gardens perform over time and if that performance could be improved upon through regular maintenance tasks could save those MS4s installing rain gardens money and effort in the long run. While the frequency of particular maintenance tasks would be site specific, a methodology has been outlined in this manuscript to determine what specific tasks may be required. The expected length of time over which rain gardens can successfully treat stormwater runoff is also unknown and if certain measures or periodic maintenance tasks could extend this time has yet to be determined. While there are many benefits to the use of rain gardens as a stormwater BMP understanding their performance over time would allow for better watershed management decisions.

As the number of rain gardens being installed increases the need for a greater understanding of their complex functions to treat stormwater runoff also increases. Scientific research will allow for improved design, maximum treatment efficiency, longevity, and minimal cost and effort associated with their maintenance. The four-level assessment approach described in this manuscript offers a unique opportunity to collaborate on research through the use of a standardize approach for quantifying rain garden performance.

11. References

Asleson, B.C., R.S. Nestingen, J.S. Gulliver, R.M. Hozalski, J.L. Nieber. 2007. Assessment of infiltration at a rain garden. In /Assessment of Stormwater Best Management Practices/, ed. J. S. Gulliver and J.L. Anderson. University of Minnesota Water Resources Center, St Paul, MN.

Baker, L.A., B.C. Asleson, and R.M. Hozalski. 2007. Analysis of water and soils. In Assessment of Stormwater Best Management Practices, ed. J. S. Gulliver and J.L. Anderson. University of Minnesota Water Resources Center, St Paul, MN.

Booth, D.B., and C.R. Jackson. 1997. Urbanization of aquatic systems: Degradation thresholds, stormwater detection, and the limits of mitigation. *Journal of the American Water Resources Association.* 33(5):1077-1090.

Buttle, J. M., and House, D. A. 1997. Spatial variability of saturated hydraulic conductivity in shallow macroporous soils in a forested basin. *Journal of Hydrology*, 203(1-4), 127-142.

Decagon Devices, Inc. 2005. Minidisk Infiltrometer User's Manual (Version 1.4). Pullman, WA.

Dietz, M.E. and J.C. Clausen. 2005. A field evaluation of rain garden flow and pollutant treatment. *Water, Air, and Soil Pollution.* 167:123-138.

Dorsey, J.D., A.D. Ward, N.R. Fausey, and E.S. Bair. 1990. A Comparison of Four Field Methods for Measuring Saturated Hydraulic Conductivity. *Transactions of the ASAE.* 33(6): 1925-1931.

Eldridge, D. J., and Freudenberger, D. 2005. Ecosystem wicks: woodland trees enhance water infiltration in a fragmented agricultural landscape in eastern Australia. *Austral Ecology*, 30, 336-347.

Erickson, A., B. Asleson, J. S. Gulliver, and R. Hozalski. 2007. Biologically enhanced practices. In Assessment of Stormwater Best Management Practices, ed. J. S. Gulliver and J.L. Anderson. University of Minnesota Water Resources Center, St Paul, MN.

Erickson, A., P. Weiss, J. S. Gulliver, R. Hozalski and B. Asleson. 2007. Developing an assessment program. In Assessment of Stormwater Best Management Practices, ed. J. S. Gulliver and J.L. Anderson. University of Minnesota Water Resources Center, St Paul, MN.

Foth, H.D. 1990. Fundamentals of Soil Science, 8E. John Wiley & Sons, Inc., New York, NY.

Gulliver, J.S. and J.L. Anderson. 2007. Assessment of Stormwater Best Management Practices. University of Minnesota, St. Paul, MN.

Halabuk, A. 2006. Influence of different vegetation types on saturated hydraulic conductivty in alluvial topsoils. *Biologia*, 61(19), S266-S269.

Hillel, Daniel. 1998. Environmental Soil Physics. Academic Press, Amsterdam.

Johnson, S.M. 2006. Evaluation of the Philip-Dunne Permeameter in determination of the effectiveness of alternative storm water practices, Plan B, University of Minnesota, St. Paul.

Klute, A. 1986. Methods of Soil Ananlysis, Part I. Physical and Mineralogical Methods, 2nd edition. Soil Science Society of America, Inc. Publisher, Madison.

Kodesova, R., Kodes, V., Zigova, A., and Simunek, J. 2006. Impact of plant roots and soil organisms on soil micromorphology and hydraulic properties. *Biologia*, 61(19), S339-S343.

Maidment, D.R. (1993). Handbook of Hydrology. McGraw-Hill, Inc., New York, NY.

Munoz-Carpena, R., C. M. Regalado, J. Alvarez-Benedi, and F. Bartoli. 2002. Field evaluation of the new Philip-Dunne permeameter for measuring saturated hydraulic conductivity. *Soil Science.* 167:9-24.

MPCA (Minnesota Pollution Control Agency). 2001. Stormwater Phase II Final Rule: MS4 Stormwater Program Overview. Publication # Wq-sw1-04. St. Paul, MN http://www.pca.state.mn.us/water/tmdl/index.html.

MPCA (Minnesota Pollution Control Agency). 2006. 2006 Impaired Water List. http://www.pca.state.mn.us/water/tmdl/index.html.

Minnesota Stormwater Steering Committee. 2005. The Minnesota Stormwater Manual. Developed by Emmons and Olivier Resources for the Stormwater Steering Committee, Minnesota Pollution Control Agency, St. Paul, MN. http://www.pca.state.mn.us/water/stormwater/stormwater-manual.html.

Nestingen, R. S. 2007. The calibration of infiltration devices and modification of the Philip-Dunne permeameter for the assessment of rain gardens, M.S. Thesis, University of Minnesota, Minneapolis.

Nestingen R., B. Asleson, J. Gulliver, R. Hozalski, J. Nieber. 2007. Techniques to assess rain gardens as stormwater best management practices. In/Modeling of Urban Water Systems, Monograph 16/, ed. W. James, K. N. Irvine, E. A. McBean, R. E. Pitt and S. J. Wright, CHI, Guelph, Ontario.

Philip, J. R. 1993. Approximate Analysis of Falling-Head Lined Borehole Permeameter. *Water Resources Research*. 29(11);3763-3768.

Prince George's County. 2002. Bioretention Manual. Programs & Planning Division Department of Environmental Resources, Maryland. http://www.goprincegeorgescounty.com/Government/AgencyIndex/DER/ESD/Bioretention/bioretention.asp?nivel=foldmenu(7).

Prince George's County, Maryland. June 1999. Low Impact Development Design Strategies. Programs & Planning Division Department of Environmental Resources, Maryland.

Rawls, W.J., D. Gimenez, and R. Grossman. 1998. Use of Soil Texture, Bulk Density, and Slope of the Water Retention Curve to Predict Saturated Hydraulic Conductivity. *Transactions of the ASAE* 41(4): 983-988.

Reynolds, W.D. and D.E. Elrick. 1991. Determination of Hydraulic Conductivity using a Tension Infiltrometer. *Soil Sci. Soc. Am. J.* 55:633-639.

Reynolds, W.R., B.T. Bowman, R.R. Brunke, C.F. Drury, and C.S. Tan. 2000. Comparison of Tension Infiltrometer, Pressure Infiltrometer, and Soil Core Estimates of Saturated Hydraulic Conductivity. *Soil Sci. Soc. Am. J.* 64: 478-484.

Richardson, J. L., and M. J. Vepraskas. 2001. Wetland Soils: Genesis, Hydrology, Landscapes, and Classification. Lewis Publishers, Boca Raton.

Saxton, Keith E. and Walter Rawls. Soil Water Characteristics: Hydraulics Property Calculator. USDA Agricultural Research Service and USDA-ARS, Hydrology and Remote Sensing Laboratory. Accessed March 2007. http://hydrolab.arsusda.gov/soilwater/Index.htm

Shaw, D. and R. Schmidt. 2003. Plants for Stormwater Design: Species Selection for the Upper Midwest. Minnesota Pollution Control Agency, St. Paul, MN.

Soilmoisture Equipment Corp. 1991. Operation Instrcutions for the Guelph Permeameter 2800KI. Santa Barbara, CA.

U.S. EPA. (2002). Urban Stormwater BMP Performance Monitoring, 821-B-02-001, Washington D.C. http://epa.gov/waterscience/stormwater/monitor.htm

Wang, L., J. Lyons, P. Kanehl, and R. Bannerman. 2001. Impacts of Urbanization on Stream Habitat and Fish across Multiple Spatial Scales. *Environmental Management* 28(2): 255-266.

Warner, G. S., and Young, R. A. 1991. Measurement of preferential flow beneath mature corn. Preferential Flow: Proceedings of the National Symposium. American Society of Agricultural Engineers, St. Joesph, MI.

Appendix A: Soil properties and constituents to consider for stormwater BMP assessment

This section addresses the measurement of soil properties and the constituents commonly found in soils of stormwater treatment practices. There may be several methods available for each analysis, only the most commonly used methods will be discussed. Detailed description of the following analysis can be found in the Methods of Soil Analysis Part 1 and Part 2.

A.1. Soil Properties

Soils are an integral component to a variety of stormwater best management practice and provide numerous functions for the treatment of stormwater runoff. Some of the critical processes that soil facilitates include: infiltration, filtration, absorption, evaporation, adsorption, nitrification, volatilization, thermal attenuation, degradation, and decomposition (Prince George's County 2002). Efficient treatment of the stormwater runoff by soil processes requires properly functioning and stable soils. Therefore measurement and understanding of soil properties are important for the overall assessment of stormwater BMPs. These processes and the physical properties of the soil change with soil depth which should be taken into consideration when examining the soil.

Bulk Density

Bulk density is the ratio of the mass of solids to the total soil volume and is used to convert gravimetric moisture content to volumetric moisture content, to calculate porosity and void ratio for a known particle density, and to gauge the degree of compaction. The bulk density of soil changes frequently and is influenced by soil structure due to its looseness or degree of compaction and by its swelling and shrinking characteristics (Hillel 1998). Bulk density is typically measured using the core method which involves drying and weighing a soil sample of a known volume. The clod method is another technique used in which the total volume is determined by coating a stable clod, or coarse peds with a water-repellent substance which is weighed in the air and then in a liquid (Klute 1986).

Soil Texture

Many of the physical and chemical properties of the soil are impacted by its' texture (Pepper et al. 1996). Soil texture is based on the particle size distribution (PSD) of sand, silt, and clay and are assigned different classes based on this ratio. The particle size distribution of soil is measured using particle-size analysis (PSA). The particle sizes are divided into three size classes; sand, silts and clays according to the U.S. Department of Agriculture (USDA) classification, however there are other classification systems used by other organizations such as the American Society for Testing and Materials (ASTM) and the International Soil Science Society (ISSS). It is recommended that pretreatment of the soil be conducted prior to PSA to improve the separation and dispersion of aggregates (Klute 1986). There are three methods available for the dispersion of soils; chemical, physical and ultrasonic. See Soil Science Society of America Book Series: 5, Methods of Soil Analysis, Part 1—Physical and Mineralogical Methods for detailed description of each method. After pretreatment of the soil sample the sand fractions are separated out using various sized mesh sieves. The fraction of silts and clays can be determined using the pipet method. The pipet method, a direct sampling procedure, is a sedimentation analysis which relies on the relationship of settling velocity and particle diameter and uses Stokes' Law settling times for sampling at a given depth for a particular temperature (Klute 1986). The hydrometer method also applies Stokes' Law and uses a calibrated hydrometer for multiple measurements of the suspended sediment. In addition to laboratory analysis for the determination of PSD, there is a field technique based on feel which is described in chapter 11 of the *Assessment of Stormwater Best Management Manual*.

Porosity

The pore spaces in the soil matrix vary in amount, size, shape, tortuosity and continuity and are an important physical property of the soil, especially the retention and transport of solutions, gases and heat (Klute 1986). Porosity is a term that refers to the volume fraction of pores and typically ranges from 0.3 to 0.6 (Hillel 1998). When the particle density (ρ_s) and the dry bulk density (ρ_b) are known the porosity (f) can be calculated using equation 6.1, a typical mineral soil has a particle density of 2.65 g/cm^3. Methods for the direct measurement of porosity can be found in Soil Science Society of America Book Series: 5, Methods of Soil Analysis, Part 1—Physical and Mineralogical Methods.

$$f = \left(1 - \frac{\rho_b}{\rho_s}\right)$$

Equation A.1

Penetrability

Compaction of soils can occur due to normal stresses and can be induced by machinery. Soils which are highly compacted exhibit low total porosity due to reduced volume and continuity of large pores; this restricts aeration, and impedes root penetration, infiltration and drainage (Hillel 1998). A direct measure of the level of compaction is done with penetrometers which measure the ease with which an object can be driven into the soil. The penetration resistance measured is influenced by several soil factors which include: water content, bulk density, compressibility, soil strength, and soil structure (Klute 1986). Chapter 11 of the *Assessment of Stormwater Best Management Practices Manual* has additional references for measuring compaction.

Water Content

The amount of water in the soil influence numerous soil properties, governs the air content and gas exchange of the soil, affects plant growth, influences microbial activity, and dictates the chemical state of the soil (Hillel 1998). The measurement of water content is also necessary for the determination of hydraulic conductivity of the soil when using a Modified Philip-Dunne infiltrometer as described in Appendix C of the *Assessment of Stormwater Best Management Manual*. There are both indirect and direct methods for measuring water content. The traditional method is the gravimetric technique and involves weighing the wet sample, drying the sample in an oven or microwave, and reweighing the sample to determine the amount of water removed. The indirect methods rely on the relationship between water content and certain physical and physical-chemical properties of the soil (Klute 1986). Electrical resistance, capacitance, neutron scattering, gamma-ray absorption, and time-domain reflectrometry (TDR) are the indirect methods used to measure water content. There are several capacitance and TDR probes available that can be used in the field with monitoring equipment or manually.

Hydraulic Conductivity

Hydraulic conductivity of soil is a measure of its ability to transmit water and is used in Darcy's law to calculate flow or infiltration rates (Klute 1986). The term permeability and hydraulic conductivity are sometimes used synonymously, however permeability is an exclusive property of the soil matrix and hydraulic conductivity includes properties of the fluid as well (Hillel 1998). Chapter 4 of the *Assessment of Stormwater Best Management Practices Manual* discusses the theory of infiltration and describes the devices used to measure infiltration in detail.

Other Soil Properties

The analysis of other soil properties such as water potential, evaporation rate (see chapter 4 also), temperature, and air permeability may also be desirable for assessment. For detailed standard procedures see Soil Science Society of America Book Series: 5, Methods of Soil Analysis, Part 1—Physical and Mineralogical Methods.

A.2. Soil Constituents

Stormwater runoff carries various types of pollutants with it and is then conveyed to a treatment practice. Measuring the type of pollutants and their concentration in the soils can be a useful assessment tool for understanding the soils capacity to retain those constituents. Retention (or sorption) is one of the major processes influencing the transport of pollutants in soil (Pepper 1996). The retention and transformation of pollutants is desirable to prevent water quality issues in lakes, streams, and rivers. To ensure that these constituents are being treated properly and that the soil has not reached its' capacity for such treatment, analysis of the soils within the practice may be necessary. The mobility of pollutants and the physical properties influencing their transport vary spatially; this should be taken into consideration when taking soil samples for analysis. This section will discuss some of the key pollutants found in soils of stormwater BMPs.

Cation Exchange Capacity

The cation exchange capacity (CEC) of soil is a major sorption mechanism for pollutants and is due primarily to the negative charge associated with clay particles and organic particles. Positively charged ions such as heavy metals are attracted to the negatively charged sites on the clay particles and therefore influence the mobility of those cations. As plants and microorganisms utilize these ions in the soil solution, exchanges are made from the negatively charged particles (soil colloids) to the soil solution (Pepper 1996). The CEC is the sum of the exchangeable cations of the soil and is usually expressed as milliequivalents of positive charge per 100 grams of soil (mEq (+) $100g^{-1}$). There are several methods available for measuring CEC; common methods include the saturation of the exchange complex with a particular cation and then measuring the absorbed cations (Black 1965). Two of these methods can be found in Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties.

Soil pH

Soils with high concentrations of organic matter and in areas with high rainfall tend to be acidic (<5.5). The pH of the soil can influence the degree of ionization of compounds which affects their solubility and may be critical to the transport of pollutants through the soil (Pepper 1996). The measurement of soil pH is split into two groups: the colorimetric methods which utilize dyes or acid-base indicators and electrometric methods that utilize an electrode to measure the hydrogen ions (Black 1965).

Organic Matter

Organic matter can affect the physical properties of soil such as aeration and infiltration by increasing soil structure due to enhanced microbial activity. The humic and nonhumic substances in organic matter contributes to the pH-dependent CEC of the soil which is important for the sorption of pollutants, and these substances can also be important for the chelation of heavy metals. Plant residues are incorporated into the soil surface and are degraded by microorganisms into complex residues which are utilized by plants and microbes for metabolism and also incorporated into macromolecules (Pepper 1996). There are direct and indirect methods used to measure the amount of organic matter present in the soil. Indirect methods typically include the measurement of organic carbon using wet or dry combustion of the material and the measurement of the amount of carbon dioxide evolved. These methods however are limited by the understanding of the ratio of organic matter to organic carbon (Black 1965). There are two primary methods that will destroy the organic material and not the inorganic portion of the soil (about 90% or more of the weight of the soil): oxidation of the organic matter and the ignition of the soil at a high temperature (750 °C).

Salinity

Soil salinity refers to the concentration of soluble salts which is harmful to plants by reducing the osmotic potential of the soil solution and restricting the plants ability to uptake water. The accumulation of salts in soils also indirectly effects soil properties such as swelling, porosity, water retention, and permeability (Hillel 1998). In practice with vegetation the soil salinity may be a necessary parameter to measure for assessment. A common method for measuring salinity is by electrical conductivity and is typically expressed as millimho per centimeter (Black 1965). According to the U.S. Department of Agriculture *Handbook 60* a saline soil has an electrical conductivity exceeding 4 mmho/cm at 25 °C (Hillel 1998).

Phosphorus

Nutrients are necessary for plant growth, however the overuse and incorrect use of fertilizers has resulted in excess nutrients being transported by groundwater or stormwater runoff (Prince George's County 2002). Phosphorus poses a particular problem in this region to surface waters as it is often the limiting nutrient restricting algal and plant growth. Phosphate anions are typically strongly bound to soil colloids and therefore immobile as they react with ions such as iron or calcium and form insoluble precipitates (Pepper 1996). In areas with high water tables, or where soil erosion is occurring phosphorus is often a primary pollutant of concern. There are both soluble and insoluble forms of phosphorus that can be measured (see chapter 2 of the *Assessment of Stormwater Best Management Practices Manual* for further discussion). See Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties for the analysis procedures of total phosphorus and organic phosphorus in soils.

Nitrogen

Nutrients such as nitrogen, phosphorus, and potassium are taken up in large quantities by plants and termed macronutrients. As mentioned in Chapter 3 of the *Assessment of Stormwater Best Management Practices Manual* under the section of constituent groups of water, nitrogen is found in numerous forms. Plants typically take up nitrogen as ammonium (NH_4^+) or nitrate (NO_3^-) which are obtained directly from dissolving salts or indirectly through processes such as nitrogen fixation (conversion of atmospheric nitrogen to ammonia) or nitrification (oxidation of ammonia and ammonium to form nitrate) (Pepper 1996). Nitrate is highly soluble and has the potential to leach into groundwater where high concentrations can result in "blue baby disease". A biological process called denitrification converts nitrate into nitrogen gas (N_2) and is discussed in chapter 2 of the *Assessment of Stormwater Best Management Manual*. There are several methods for the analysis of the various forms of nitrogen and the appropriate technique should be chosen depending on the species of interest.

Metals

Some of the metals commonly found in stormwater are: lead, zinc, copper, and cadmium. Zinc and copper are micronutrients necessary for plant growth, however when found in high concentrations they can be toxic to plants. The typical copper content found in soils ranges from 1 to 3 parts per million (ppm) and ranges from 10 to 300 ppm for zinc concentrations (Black 1965). The most toxic metals which are nonessential to plants include: cadmium, lead, and mercury. These are referred to as heavy metals. Microorganisms in the soil have developed a resistance to these metals and also have the ability to transform some of the metals through oxidation/reduction (redox) reactions, complexation, and alkylation (Pepper 1996). There is the potential for the accumulation of metals in stormwater BMPs and may therefore be considered for an assessment program. The analysis procedures for metals considered to be micronutrients can be found in Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties, while the analysis for heavy metals are highly specialized and require expertise.

Microbial Populations

The soil contains billions of living organisms which are essential to biochemical transformations and the overall health of the soil. The major groups of organisms found in soils include bacteria, actinomycetes, fungi, algae, viruses and macro fauna (Pepper 1996). The vital role these microbial populations play in the soil environment make their presence and diversity necessary for the proper treatment of stormwater runoff. Due to the variability in the type of microorganisms present in the soil and the special requirements for each species, it is difficult to directly measure the biological community in the soil. The most-probable-number (MPN) method allows for the estimation of the population density without direct measurement of actual colonies (Black 1965). There are additional techniques for measuring specific microorganisms that can be found in Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties. The abundance of microorganisms in the soil, and therefore pollutant biodegradation is dependent on oxygen and nutrient availability, organic matter content, pH, redox potential, temperature, soil moisture and soil texture (Pepper 1996).

A.3. References

Pepper, I. L., C. P. Gerba, and M. L. Brusseau. 1996. Pollution Science. Academic Press, San Diego.

Prince George's County. 2002. Bioretention Manual. Programs & Planning Division Department of Environmental Resources, Maryland. http://www.goprincegeorgescounty.com/Government/AgencyIndex/DER/ESD/Bioretention/bioretention.asp?nivel=foldmenu(7).

Hillel, Daniel. 1998. Environmental Soil Physics. Academic Press, Amsterdam.

Klute, A. 1986. Methods of Soil Ananlysis, Part I. Physical and Mineralogical Methods, 2nd edition. Soil Science Society of America, Inc. Publisher, Madison.

Black, C. A. 1965. Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties, Number 9 in the series AGRONOMY. American Society of Agronomy, Inc. Publisher, Madison, WI.

Appendix B: Spatial Variability of Saturated Hydraulic Conductivity

B.1. Introduction

The treatment of stormwater runoff in urban areas for improved water quality and flood control has become necessary and mandatory in some cities. A commonly used stormwater best management practice (BMP) in urban areas is rain gardens. Rain gardens are a terrestrial-based, water quality and water quantity control process that are often integrated with other low impact development (LID) practices that aim to mimic pre-development hydrology. The critical processes that rain gardens provide in the treatment of stormwater include: infiltration, interception, settling, evapotranspiration, filtration, absorption, adsorption, assimilation, nitrification, denitrification, volatilization, thermal attenuation, degradation and decomposition (Prince George's County, Maryland 2002). The primary process of rain gardens is to infiltrate stormwater runoff through the soil. The stormwater runoff is often captured through curb cuts or storm sewer inlet structures. Areas where the native soils have low permeability or where groundwater recharge is not desired underdrains may be installed beneath the soil. The combination of soil and plants allows for multifunctional treatment of the runoff and contributes to the aesthetics of these stormwater BMPs. For this reason rain gardens are of great interest to a number of stakeholders. Often these stormwater BMPs are designed and installed without a comprehensive understanding of their integrate function. This research investigates the driver of infiltration, the saturated hydraulic conductivity (K_{sat}) of several rain gardens.

B.2. Literature Review

Rain gardens are typically designed to drain within a specified time (24 to 48 hours) therefore knowing the K_{sat} is desired to assess its performance. Hydrologic modeling has also increased the demand for accurate measurements of K_{sat} and is important for the management of ecosystems (Vauclin et al., 1994). The high spatial variability of K_{sat} found in the field can create problems when determining K_{sat} in situ or using laboratory techniques (Mallants et al., 1997). Laboratory methods for measuring K_{sat} utilize Darcy's law in one dimension on undisturbed soil columns collected from the field. Some disadvantages of laboratory methods include the introduction of artefacts due to soil disturbance and loss of natural conditions present in the field (Regalado and Muñoz-Carpena, 2004). K_{sat} values measured using laboratory techniques are influenced by column size (Mallants et al., 1997). Mallants et al. (1997) evaluated the spatial variability of laboratory K_{sat} measurements using three different sized columns. They concluded that the geometric mean of K_{sat} decreased as the column size increased and suggest that in situ measurements of K_{sat} may be preferred over laboratory techniques. Arya et al. (1998) measured K_{sat} of a field plot using both collected soil cores and a large scale irrigation field procedure. The lab measurements of the pre-saturated subsoil cores had K_{sat} values 360 to 860 times lower than the field measured values. Munoz-Carpena et al. (2002) reported that the Philip-Dunne permeameter provided an inexpensive and quick field method for measuring K_{sat} in the field. This device was compared to two other well-established permeameters, the laboratory and the Guelph. The Philip-Dunne permeameter was selected as superior in terms of cost, preparation time and ease of operation. Further evaluation and modification to the Philip-Dunne permeameter field method was conducted by Nestingen et al. (2007). Nestingen (2007) determined that the new Modified Philip-Dunne (MPD) infiltrometer was ideal for measuring the surface K_{sat} of rain gardens and other stormwater BMPs.

Numerous studies have indicated that K_{sat} is one of the most highly variable soil properties. The high variability of K_{sat} in the field has been attributed to macroporosity, and local changes in particle size distribution and bulk density (Tsegaye et al., 1998). Macropores are the interaggregate cavities that may be several millimeters or even centimeters in width and serve as the primary avenues for infiltration and drainage of water and for aeration (Hillel, 1998). These large voids are formed by the shrinking and swelling action of clays, freezing and thawing cycles, decaying roots, erosive action, and biological activity such as earthworms, insects or burrowing animals. The fraction of soil volume comprised of macropores is referred to as macroporosity. Macropores typically constitute a small portion of the total porosity however small changes in macroporosity are known to produce a significant change in flux (Germann and Beven, 1981) and under some conditions may dominate vertical flow rates during infiltration (Chen and Wagenet, 1992). A strong linear relationship between initial infiltration rates and soil macroporosity in clayey soils was reported by Lin et al. (1998). Buttle and McDonald (2000) determined the surface macroporosity and examined its relationship with the movement of water and solutes within the soil profile. Their hypothesis that there is a direct relationship between surface-derived macroporosity and the potential for infiltration via preferential flow within the profile was partially supported by their experiments. Flow through macropores is initiated under ponding conditions and the flow rate is affected by water content at time of activation and the time interval between activation (Ruan and Illangasekare, 1998). This indicates that flow through a single macropore decreases with time and that activation of macropores is not uniform contributing to the high variability of K_{sat}. Macropores which effectively conduct water to deeper depths depends on both accessibility of free water to the openings of macropores and their continuity to an open exit (Munyankusi et al., 1994). The role of macropores in the transport of water and chemicals is well documented (Beven and Germann 1982) and of special interest when considering the use of stormwater BMPs designed to facilitate infiltration.

Forest soils are known to contain an abundance of macropores in the surface layers due to high root mass and biological activity (Buttle and House, 1997). Other highly vegetated systems such as rain gardens may exhibit a similar abundance of root biomass and biological activity. Various species of earthworms burrow at various depths and in both the horizontal and vertical direction and a particular earthworm species creates burrows 2.4 meters below the soil surface and up to 10 millimeter in diameter (Munyankusi et al., 1994). Munyankusi et al. (1994) measured macropores created by earthworms from a large soil core and found that the number of surface macropores which are continuous to deeper depths decrease with increasing soil depth. This indicates that the species of earthworms present determines the continuity of macropores to deeper depths and therefore the transport of water to deeper depths. Other burrowing fauna such as insects, moles and chipmunks may also create significant macropores in the soil. Both live and decaying plant roots can create preferential flow paths in highly vegetated areas. Plant roots can influence the K_{sat} of the topsoil directly through preferential flow or indirectly by their influence on soil structure (Halabuk, 2006). Kodešová et al. (2006) examined the impact of roots and varying organisms on the soil pore structure of soil samples taken from a depth of 60 centimeters to avoid the impacts of weather and management practices. The results indicate that the soil porous system is highly affected by plant roots and microorganisms. Warner and Young (1991) investigated the relationship of stem flow and preferential flow for mature corn. They concluded that interception and stem flow amounted to a substantial portion of the applied rainfall and that preferential flow beneath corn roots was very significant. Eldridge and Freudenberger (2005) examined the way that water moves within a woodland landscape and reported that soil water flow was substantially greater under the trees for finer textured soils. Their results indicate a sevenfold increase in infiltration between timbered and non-timbered sites, highlighting the importance of woody plants on increased infiltration. Preferential flow studies have revealed that dye moves much deeper into the soil at the base of trees and ferns (Reyonlds, 1966). Aubertin (1971) reported that the preferential flow through root channels in mixed hardwood forest soils were significant and in fact dominated flow. The influence of time of planting on the measured infiltration under flood irrigation was examined by Meek et al. (1989) on an alfalfa field. An increase in infiltration rates with time and the number and size of macropores at different depths confirms that infiltration in the field was dominated by flow through decaying root channels. Halabuk (2006) reported a significant correlation between root biomass and K_{sat} in the topsoil covered by arable crops, which were former wet meadows. However there was no significant relationship between root biomass and K_{sat} in topsoils covered by the wet meadows or the wetlands. This may be attributed to the influence of other factors such as high organic matter content, and the occurrence of large macropores. Several other factors may also influence the measured K_{sat} such as bulk density, texture, water content, organic matter content and porosity. The fluidity of the permeating liquid also influences the K_{sat} of the soil (Hillel, 1998). However, Buttle and House (1997) reported that the presence of macropores in soils overrides the influence of soil texture, total porosity and organic matter content on the bulk K_{sat} of the soil profile. Ahuja et al. (1984) determined that the effective porosity (total porosity minus field capacity of the soil) was related to K_{sat} values with considerable scatter in the relationship on two different soils. A study comparing root biomass and bulk density to K_{sat} on three different types of vegetated land demonstrated a strong negative correlation between bulk density and K_{sat} indicating that soil structure affected water transport more than root biomass itself (Halabuk, 2006). There is strong evidence that the presence of macropores can dominant flow and that physical soil properties also play a critical role in soil water flow. Research has confirmed that the variability of both physical and hydraulic properties of the soil are complex in vegetated and biologically active landscapes such as rain gardens.

It is often cited in literature that a large number of measurements are necessary to accurately describe the spatial variability the K_{sat} of the soil and to estimate the mean value of the population (Muñoz-Carpena et al., 2002; Tsegaye et al., 1998). The question of obtaining a representative mean of the K_{sat} of a rain garden may be particularly important for stormwater managers and others interested in assessing the performance of infiltration practices. Understanding how those measurements change throughout the basin may also shed light on important maintenance and performance issues relating to infiltration. Geostatistical analysis is commonly used to characterize and quantify the spatial variability of soils (Sauer et al., 2006). The spatial dependence of K_{sat} has also been investigated with the use of geostatistical tools (Regalado and Muñoz-Carpena, 2004). The high variability of K_{sat} and its important role in several processes such as the transport of pollutants, recharging of groundwater, and the survival of crops makes understanding this soil property of great interest.

B.3. Spatial Variability of K_{sat} in Rain Gardens

The ranges of the measured K_{sat} within each rain garden were highly variable at some of the sites and less so at others. The size and number of measurements which were made at each rain garden using the MPD are shown in Table B.1. The individual K_{sat} value for each test location along with the coordinates of its location is listed in Tables B.2 through B.7. Maps containing the spatial location and identification label for each test were generated using Surfer and are shown in Figures B.1 through B.7.

Table B.1. Description of rain gardens where K_{sat} was measured using the MPD infiltrometer.

Rain Garden	Size	# of measurements
Burnsville	27.87 m^2	24
Cottage Grove	72.00 m^2	20
RWMWD (1)	146.97 m^2	12
RWMWD (4)	29.08 m^2	4
RWMWD (5)	41.90 m^2	16
Thompson Lake	278.71 m^2	30
U of M, Duluth	1,347.09 m^2	33
U of M, St. Paul	66.52 m^2	40

Table B.2. Burnsville rain garden measured K_{sat} data.

Burnsville MPD Data			
ID	**Northing**	**Easting**	**K_{sat} (cm/s)**
1	4952745.12	479320.80	0.00624
2	4952744.93	479319.63	0.03521
3	4952744.70	479319.05	0.00823
4	4952744.61	479318.24	0.08148
5	4952745.14	479316.77	0.03820
6	4952747.31	479316.28	0.00486
7	4952748.34	479319.19	0.00244
8	4952748.54	479320.44	0.01548
9	4952748.48	479321.09	0.00914
10	4952748.22	479322.59	0.02138
11	4952747.07	479323.78	0.00853
12	4952746.37	479323.20	0.00055
14	4952745.71	479321.44	0.01336
15	4952745.85	479320.43	0.00548
16	4952745.84	479319.42	0.00968
17	4952746.06	479318.34	0.02112
18	4952747.03	479318.28	0.03283
19	4952747.82	479319.03	0.01441
20	4952747.94	479319.99	0.03553
21	4952747.78	479320.93	0.00378
22	4952747.19	479322.31	0.01926
23	4952746.80	479320.69	0.01293
24	4952746.55	479319.50	0.00868

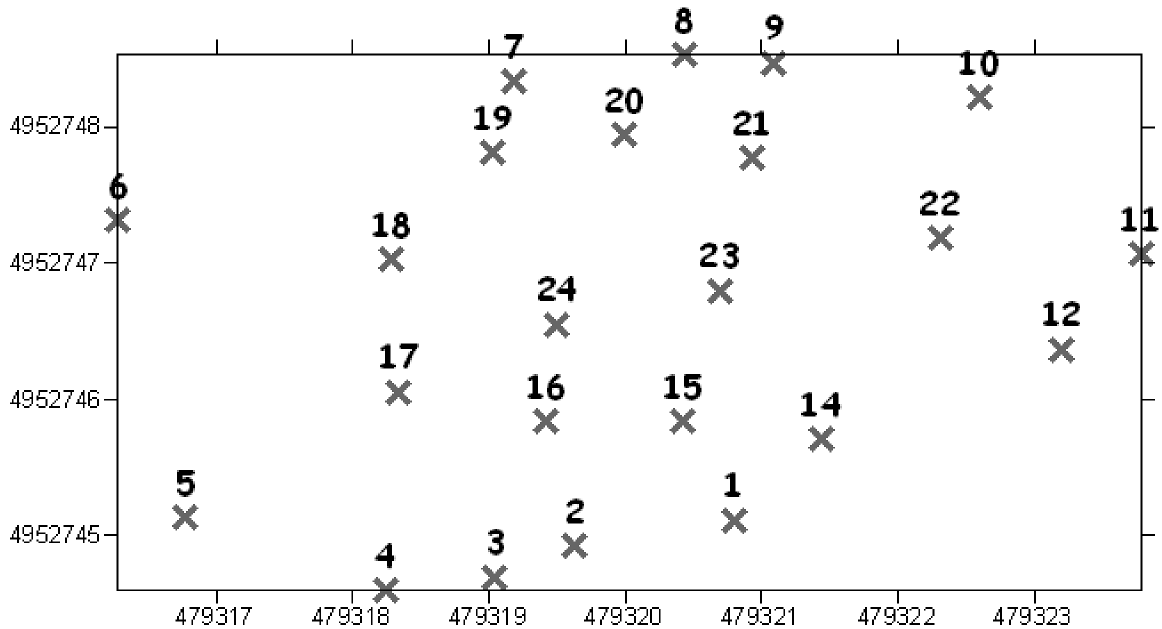

Figure B.1. Burnsville K_{sat} coordinate location map.

Table B.3. Cottage Grove rain garden measured K_{sat} data.

Cottage Grove MPD Data			
ID	**Northing**	**Easting**	**K_{sat} (cm/s)**
2	4963597.94	503505.52	0.02135
3	4963597.59	503504.66	0.04867
4	4963598.60	503506.00	0.00403
5	4963596.45	503505.48	0.02200
6	4963597.67	503506.67	0.01335
7	4963595.38	503504.10	0.01853
8	4963596.41	503507.52	0.01756
9	4963596.23	503509.21	0.01731
10	4963598.35	503508.68	0.01522
11	4963596.61	503509.13	0.02870
12	4963595.66	503508.49	0.02000
13	4963595.69	503508.13	0.02046
14	4963592.26	503508.44	0.03988
15	4963593.57	503509.01	0.01879
16	4963594.98	503510.15	0.01377
17	4963595.23	503510.96	0.04552
18	4963595.43	503511.47	0.03195
19	4963593.90	503512.11	0.05358
20	4963592.41	503509.07	0.01916
21	4963591.56	503510.78	0.00520

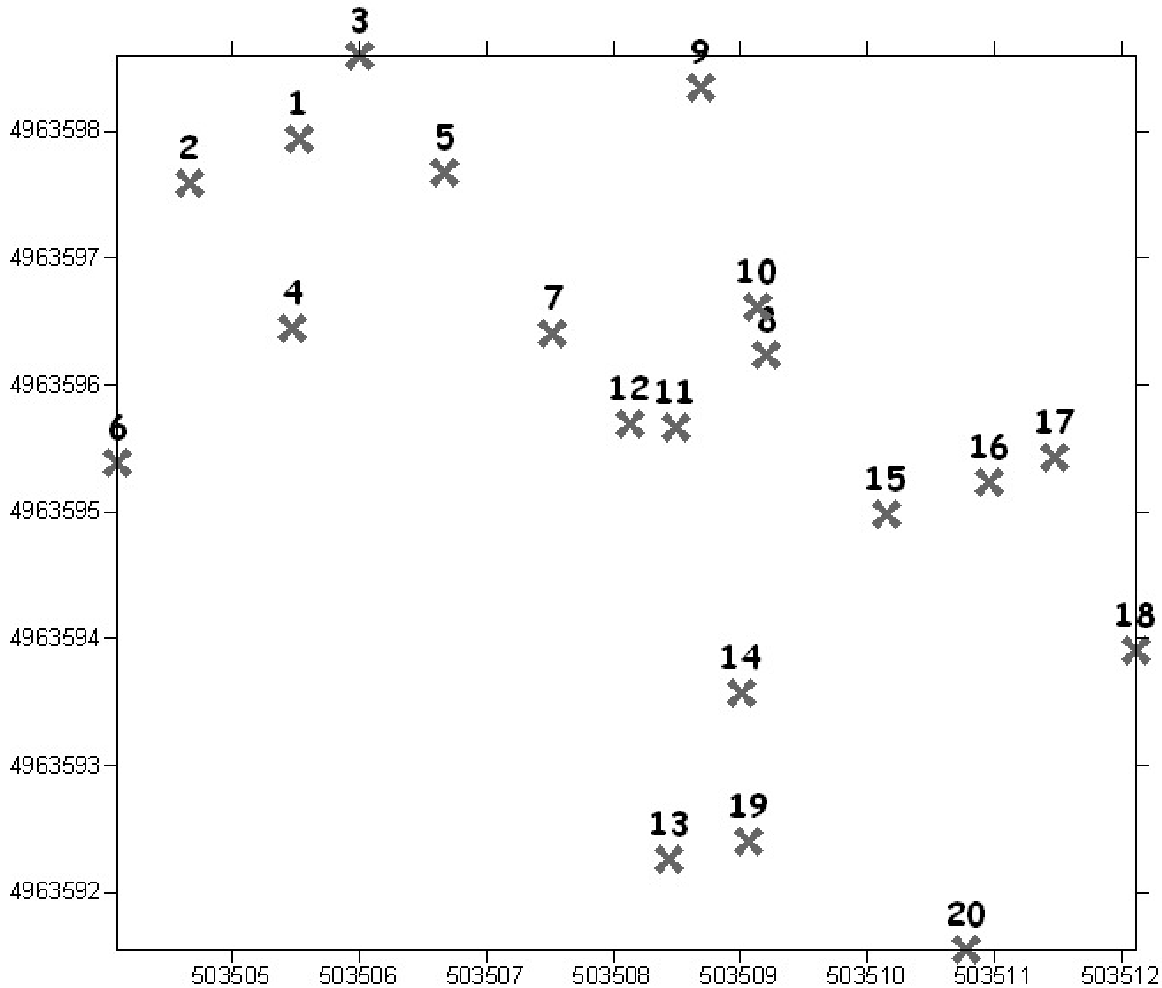

Figure B.2. Cottage Grove K_{sat} coordinate location map.

Table B.4. RWMWD rain gardens measured K_{sat} data.

RWMWD MPD Data							
ID	Northing	Easting	K_{sat} (cm/s)	ID	Northing	Easting	K_{sat} (cm/s)
5b	4985361.63	493734.54	0.00027	1a	4985354.48	493723.98	0.00239
5a	4985362.79	493733.24	0.00137	1b	4985358.07	493722.83	0.00443
5c	4985363.98	493732.02	0.00481	1c	4985357.23	493720.88	0.00082
5d	4985364.11	493735.21	0.00221	1d	4985354.09	493718.90	0.02578
5e	4985365.44	493735.27	0.00024	1e	4985357.06	493718.17	0.00151
5f	4985367.44	493732.68	0.01570	1f	4985358.85	493720.73	0.00388
5g	4985367	493736	0.00073	1g	4985358.78	493717.43	0.01572
5h	4985368.44	493737.13	0.00165	1h	4985355.73	493716.13	0.01023
5i	4985368.84	493737.02	0.00019	1i	4985358.28	493715.30	0.00721
5j	4985371.13	493736.29	0.00841	1j	4985361.04	493715.95	0.00627
5k	4985370.2	493733.5	0.01189	1k	4985362.64	493715.76	0.00723
5l	4985365.94	493733.60	0.00018	1l	4985364.05	493713.88	0.00429
5m	4985366.84	493741.26	0.00069	4d	4985350.97	493726.28	0.00419
5n	4985368.50	493735.12	0.00026	4c	4985349.40	493724.05	0.00467
5o	4985369.56	493738.72	0.00081	4b	4985346.28	493723.67	0.00382
				4a	4985347.40	493725.10	0.00001

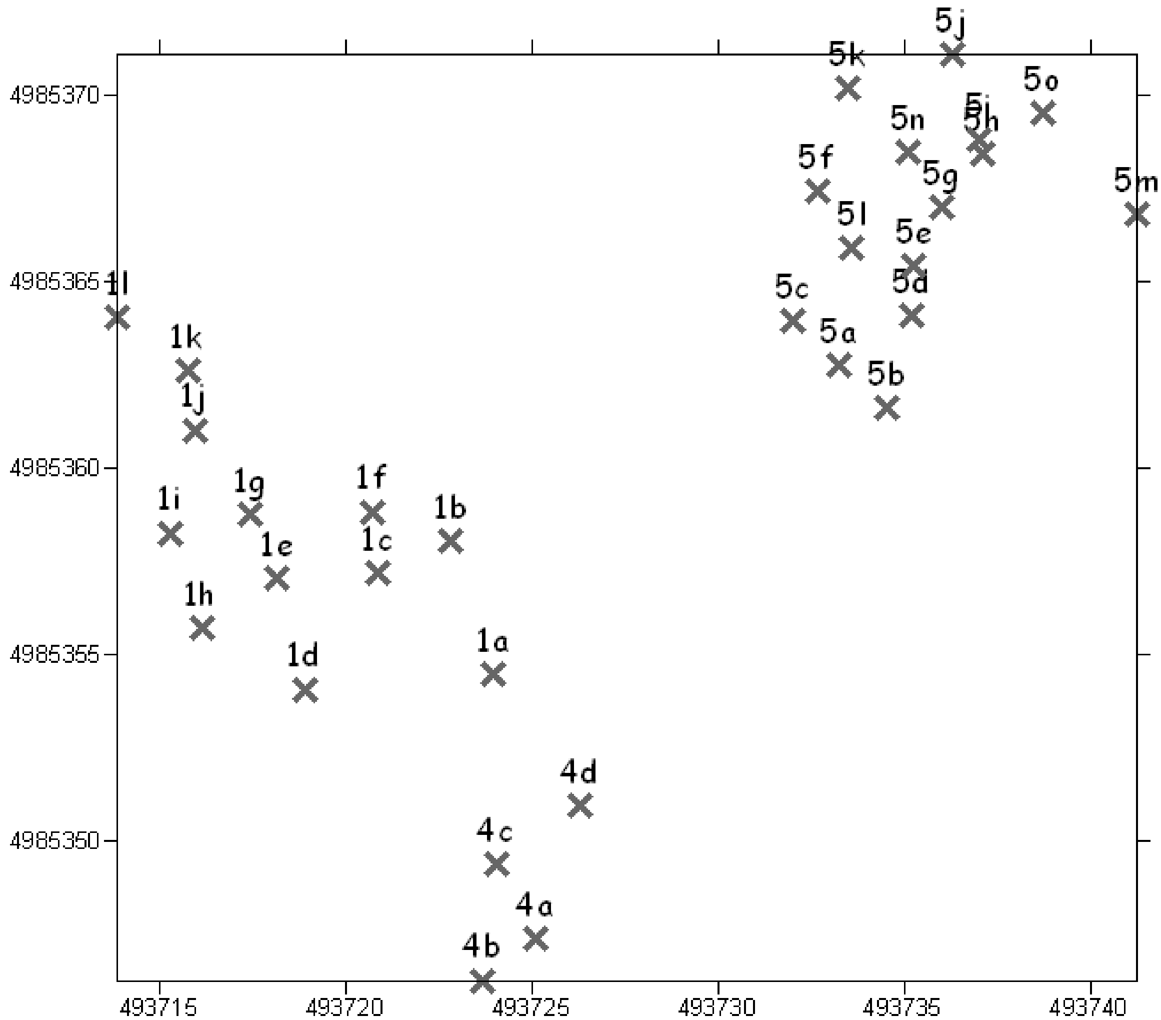

Figure B.3. RWMWD K_{sat} coordinate location map.

Table B.5. Thompson Lake rain garden measured K_{sat} data.

Thompson Lake MPD Data			
ID	Northing	Easting	K_{sat} (cm/s)
1	4973041.94	494544.28	0.00688
2	4973041.57	494540.33	0.00377
3	4973044.00	494539.90	0.01317
4	4973045.92	494542.54	0.00061
5	4973047.34	494540.67	0.0000007
6	4973045.58	494537.52	0.00441
7	4973048.24	494538.48	0.05405
8	4973050.44	494540.92	0.00075
9	4973050.55	494538.31	0.00000
10	4973050.04	494534.81	0.00192
11	4973051.62	494532.65	0.01138
12	4973053.26	494536.21	0.02304
13	4973054.31	494538.98	0.00003
14	4973056.94	494536.08	0.00628
15	4973054.28	494532.38	0.00500
16	4973055.32	494529.80	0.02270
17	4973057.13	494532.38	0.00033
18	4973059.54	494535.48	0.00291
19	4973062.09	494534.74	0.00148
20	4973060.30	494531.12	0.00561
21	4973060.20	494525.99	0.02471
22	4973062.92	494526.16	0.01871
23	4973064.85	494530.18	0.00213
24	4973065.99	494533.19	0.00401
25	4973066.29	494529.13	0.00023
26	4973065.74	494524.06	0.04790
27	4973068.33	494525.87	0.04333
28	4973070.83	494526.84	0.01550
29	4973072.00	494530.58	0.02535
30	4973070.84	494533.29	0.01614

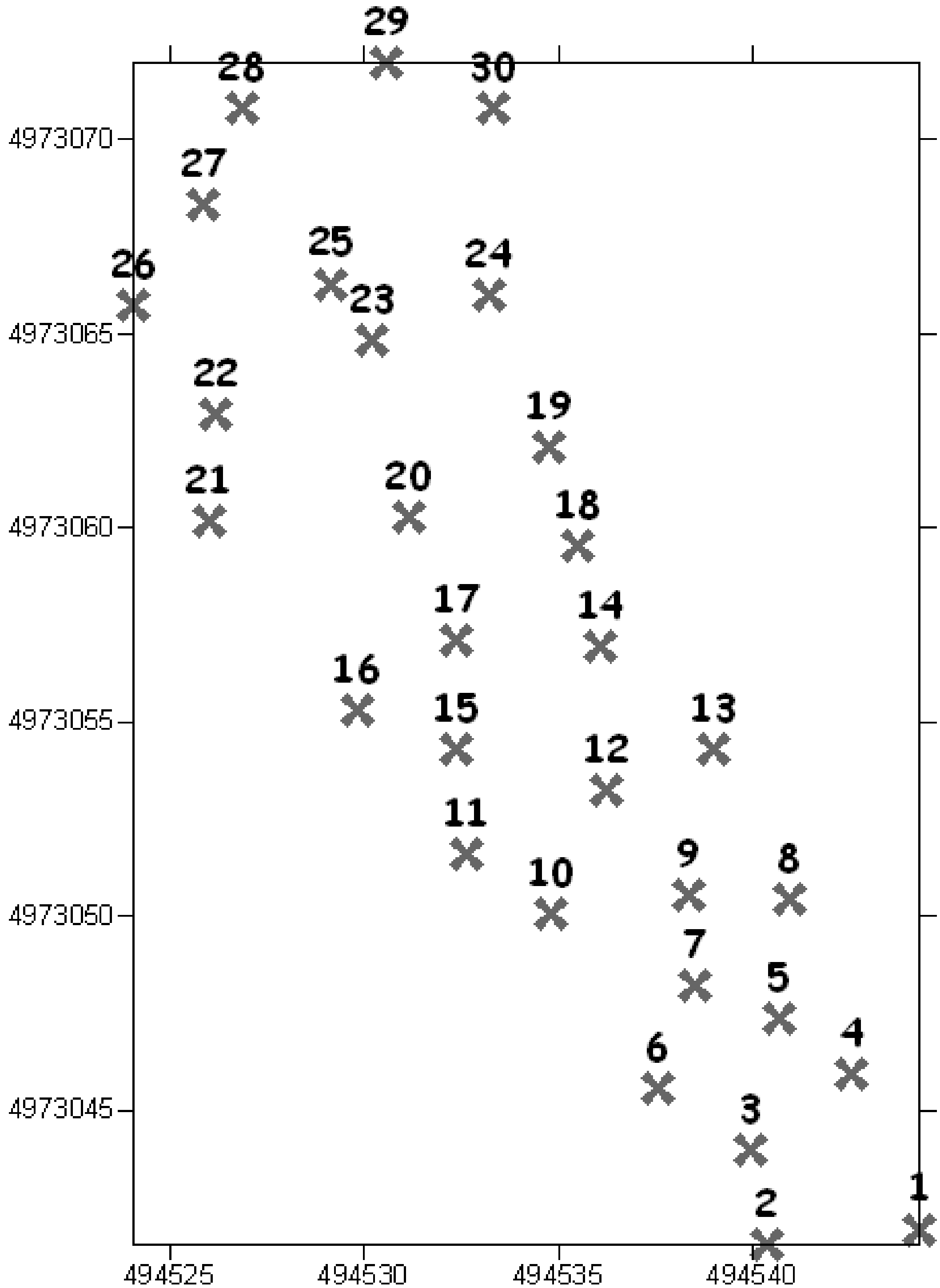

Figure B.4. Thompson Lake K_{sat} coordinate location map.

Table B.6. U of M - Duluth rain garden measured K_{sat} data.

U of M - Duluth MPD Data			
ID	Northing	Easting	K_{sat} (cm/s)
1w	5185052.15	569876.86	0.00097
2w	5185054.60	569877.83	0.00109
3w	5185053.84	569881.20	0.00173
4w	5185051.49	569879.26	0.00014
5w	5185049.20	569878.06	0.00095
7w	5185044.32	569877.10	0.00089
8w	5185047.34	569880.01	0.02882
9w	5185049.29	569881.92	0.00069
10w	5185048.19	569885.68	0.00544
11w	5185052.56	569885.51	0.00155
13w	5185049.60	569889.31	0.00255
14w	5185045.22	569888.46	0.00651
15w	5185044.11	569885.20	0.00962
16w	5185040.94	569883.59	0.00200
17w	5185042.76	569881.69	0.00104
18w	5185040.84	569879.02	0.00263
19w	5185041.49	569876.63	0.00033
20w	5185038.60	569877.96	0.00074
21w	5185046.59	569881.93	0.03484
22w	5185058.63	569877.05	0.00040
23w	5185060.95	569873.63	0.00094
12w	5185052.35	569887.62	0.01661
24w	5185033.99	569885.71	0.01647
25w	5185025.97	569892.62	0.06363
26o	5185028.03	569898.00	0.00163
27o	5185034.33	569901.75	0.00152
28o	5185022.67	569906.67	0.05923
29o	5185023.38	569910.71	0.00230
30o	5185026.07	569910.04	0.00905
31w	5185047.47	569868.52	0.00055
32w	5185041.32	569866.65	0.00139
33w	5185038.06	569858.47	0.03049
34w	5185029.26	569854.28	0.00133
35w	5185026.55	569857.29	<0.0000007

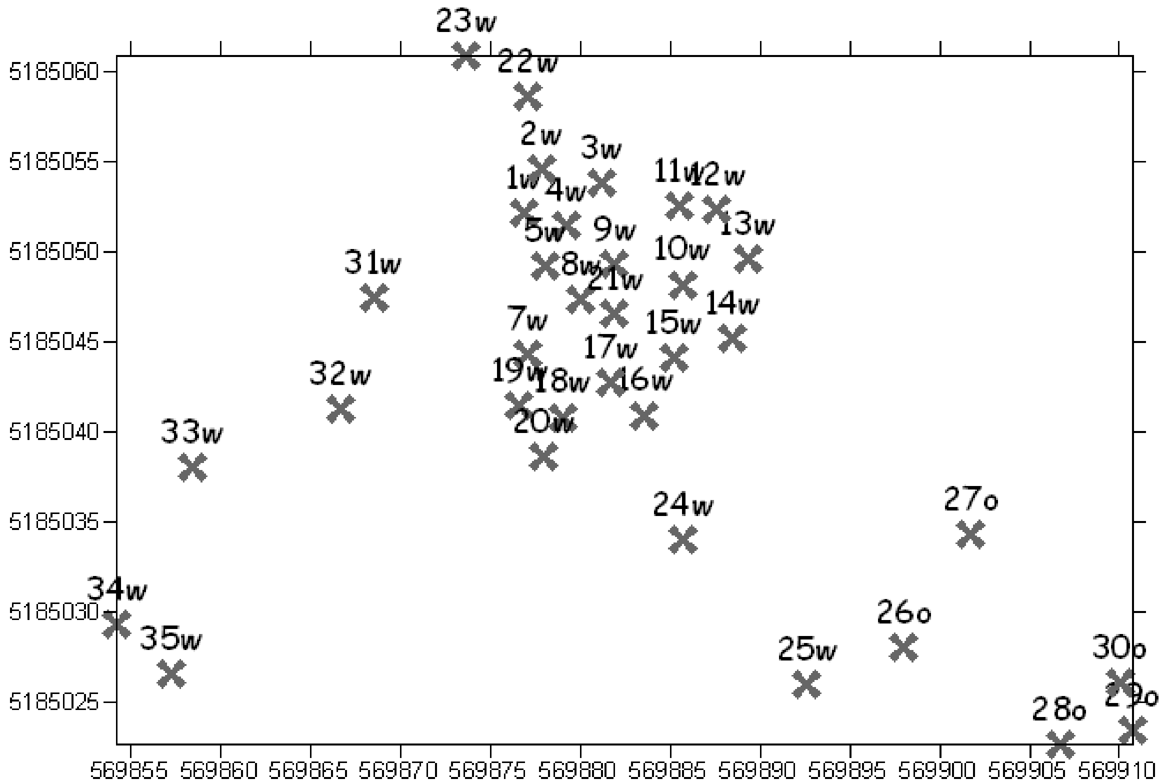

Figure B.5. U of M – Duluth K_{sat} coordinate location map.

Table B.7. U of M – St. Paul rain garden measured K_{sat} data.

U of M - St. Paul MPD Data			
ID	**Northing**	**Easting**	**K_{sat} (cm/s)**
1a	4980874.07	485677.11	0.01274
1b	4980874.07	485678.13	0.00491
1c	4980872.54	485679.23	<0.0000007
1d	4980873.55	485681.47	0.01515
1e	4980872.97	485682.19	0.01048
2e	4980870.34	485682.43	0.01335
2d	4980871.48	485681.37	0.00427
2c	4980871.41	485679.43	0.00146
2b	4980869.64	485678.13	0.00466
2a	4980870.08	485677.67	0.00539
m1	4980872.56	485679.06	0.00179
m2	4980871.08	485679.63	0.00154
m3	4980871.08	485680.83	0.00142
3a	4980869.75	485677.61	0.00749
3b	4980869.30	485678.41	0.00664
3c	4980869.86	485679.83	0.00119
3d	4980870.09	485681.44	0.00260
3e	4980869.38	485681.24	0.00715
m4	4980869.09	485679.91	0.00175
m5	4980866.82	485681.21	0.00149
m6	4980866.34	485680.17	0.00124
4a	4980867.72	485678.07	0.00567
4b	4980867.42	485678.79	0.00126
4c	4980866.95	485680.56	0.00166
4d	4980866.85	485681.50	0.00288
4e	4980867.06	485682.27	0.00889
5a	4980865.17	485678.30	0.00486
5b	4980867.32	485679.49	0.00031
5c	4980865.66	485681.27	0.00050
5d	4980865.32	485681.66	0.00299
5e	4980865.09	485682.38	0.00911
m8	4980864.07	485681.97	0.00064
m7	4980864.30	485680.53	0.00141
m9	4980863.28	485682.04	0.00166
6e	4980862.10	485682.24	0.00512
6d	4980862.18	485681.12	0.00666
6c	4980862.29	485680.15	0.00276
6b	4980862.89	485679.77	0.00408
6a	4980863.10	485678.06	0.00162

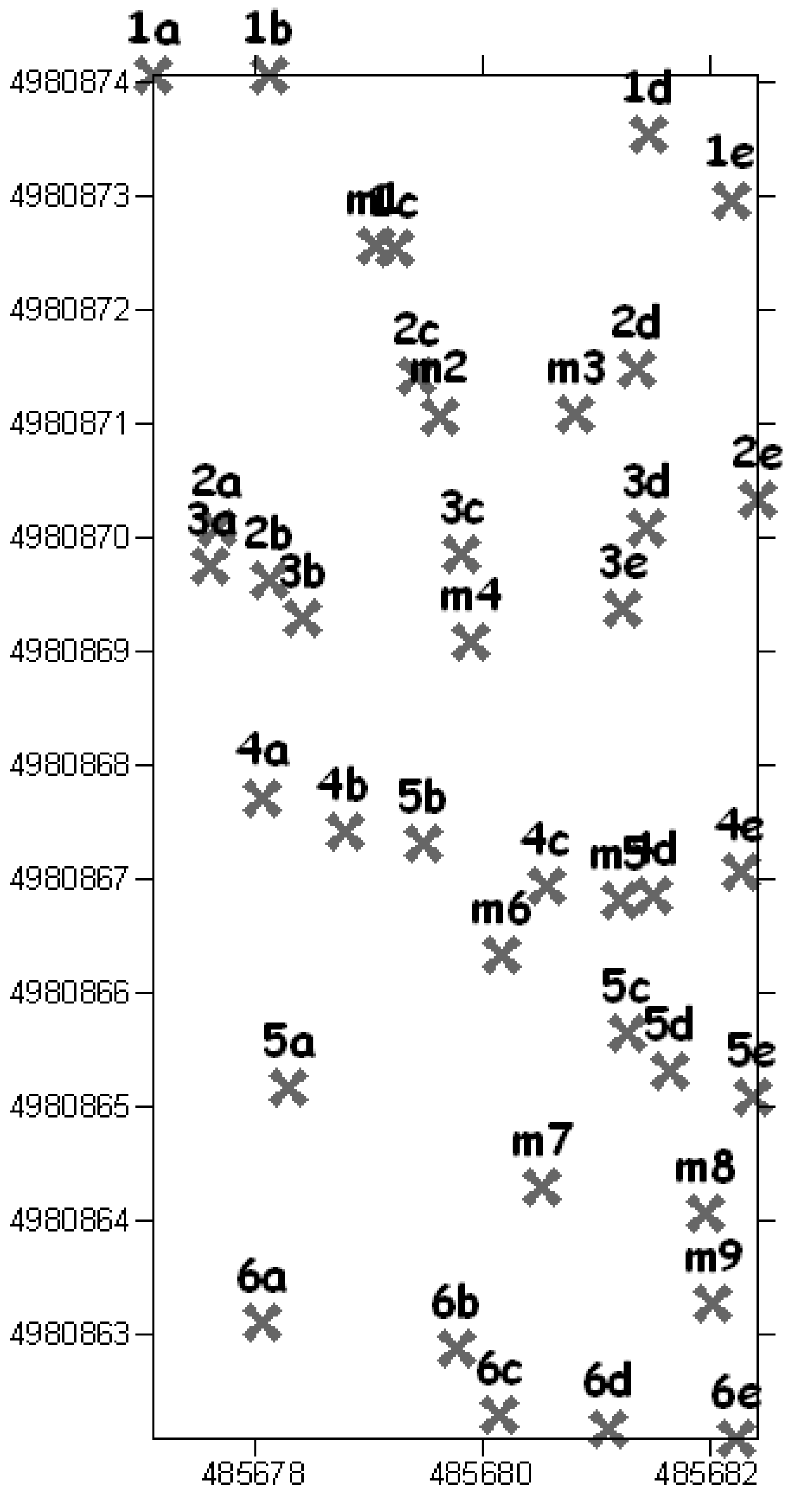

Figure B.6. U of M – St. Paul K_{sat} coordinate location map.

B.2. References

Ahuja, L. R., Naney, J. W., Green, R. E., and Nielsen, D. R. 1984. "Macroporosity to Characterize Spatial Variability of Hydraulic Conductivity and Effects of Land Management." *Soil Sci Soc Am J*, 48(4), 699-702.

Arya, M.L., Dierolf, S. Thomas, Sofyan, Agus, Widjaja-Adhi, I.P.G., van Genuchten, M.Th. 1998. "Field measurements of the saturated hydraulic conductivity of a macroporous soil with unstable subsoil structure." *Soil Science*, 163(11), 841-852.

Aubertin, G. M. 1971. "Nature and extent of macropores in forest soils and their influence on subsurface water movement." *For. Serv. Res. Pap.*, NE(U.S.) 192, 33pp.

Beven, K., and Germann, P. 1982. "Macropores and water flow in soils." *Water Resources Res.*, 18, 1311-1325.

Buttle, J. M., and House, D. A. 1997. "Spatial variability of saturated hydraulic conductivity in shallow macroporous soils in a forested basin." *Journal of Hydrology*, 203(1-4), 127-142.

Buttle, J. M., and McDonald, D. J. 2000. "Soil macroporosity and infiltration characteristics of a forest podzol." *Hydrological processes*, 14, 831-848.

Chen, C., and Wagenet, R. J. 1992. "Simulation of water and chemicals in macropore soils Part 1. Representation of the equivalent macropore influence and its effect on soilwater flow." *Journal of Hydrology*, 130(1-4), 105-126.

Eldridge, D. J., and Freudenberger, D. 2005. "Ecosystem wicks: woodland trees enahnce water infiltration in a fragmented agricultural landscape in eastern Australia." *Austral Ecology*, 30, 336-347.

Germann, P., and Beven, K. 1981. "Water flow in soil macropores: I. An experimental approach." *J. Soil Sci.*, 32, 1-13.

Halabuk, A. 2006. "Influence of different vegetation types on saturated hydraulic conductivty in alluvial topsoils." *Biologia*, 61(19), S266-S269.

Hillel, D. 1998. *Environmental Soil Physics*, Academic Press, Amsterdam.

Kodesova, R., Kodes, V., Zigova, A., and Simunek, J. 2006. "Impact of plant roots and soil organisms on soil micromorphology and hydraulic properties." *Biologia*, 61(19), S339-S343.

Lin, H.S., McInnes, K.J., Wilding, L.P., and Hallmark, C.T. 1998. "Macroporosity and initial moisture effects on infiltration rates in vertisols and vertic intergrades. *Soil Science, 163(1),2-8.*

Mallants, D., Mohanty, B. P., Vervoort, A., and Feyen, J. 1997. "Spatial analysis of saturated hydraulic conductivity in a soil with macropores." *Soil Technology*, 10(2), 115-131.

Meek, B. D., Rechel, E. A., Carter, L. M., and DeTar, W. R. 1989. "Changes in infiltration under alfalfa as influenced by time and wheel traffic." *Soil Sci. Soc. Am. J.*, 53, 238-241.

Munoz-Carpena, R., Regalado, C. M., Alvarez-Benedi, J., Bartoli, and Francois. 2002. "Field Evaluation of the New Philip-Dunne Permeameter for Measuring Saturated Hydraulic Conductivity." *Soil Science*, 167(1), 9-24.

Munyankusi, E., Gupta, S. C., Moncrief, J. F., and Berry, E. C. 1994. "Earthworm Macropores and Preferential Transport in a Long-Term Manure Applied Typic Hapludalf." *Journal of Environmental Quality*, 23(4), 773-784.
Nestingen, R. S. 2007. The calibration of infiltration devices and modification of the Philip-Dunne permeameter for the assessment of rain gardens, M.S. Thesis, University of Minnesota, Minneapolis.
Prince George's County. 2002. Bioretention Manual. Programs & Planning Division Department of Environmental Resources, Maryland. http://www.goprincegeorgescounty.com/Government/AgencyIndex/DER/ESD/Bioretention/bioretention.asp?nivel=foldmenu(7).
Regalado, C. M., and Munoz-Carpena, R. 2004. "Estimating the saturated hydraulic conductivity in a spatially variable soil with different permeameters: a stochastic Kozeny-Carman relation." *Soil and Tillage Research*, 77(2), 189-202.
Reyolds, E. R. C. 1966. "The percolation of rianwater through soil demonstrated by flourescent dyes." *J. Soil Sci. Soc.*, 70(1), 127-132.
Ruan, H., and Illangasekare, T. H. 1998. "A model to couple overland flow and infiltration into macroporous vadose zone." *Journal of Hydrology*, 210(1-4), 116-127.
Sauer, T. J., Cambardella, C. A., and Meek, D. W. 2006. "Spatial variation of soil properties relatng to vegetation changes." *Plant and Soil*, 280, 1-5.
Tsegaye, T., Hill, Robert L. 1998. "Intensive tillage effects on spatial variability of soil physical properties." *Soil Science*, 163(2), 143-154.
Vauclin, M., Elrick, D. E., Thony, J. L., Vachaud, G., Revol, P., and Ruelle, P. 1994. "Hydraulic conductivity measurements of the spatial variability of a loamy soil." *Soil Technology*, 7(3), 181-195.
Warner, G. S., and Young, R. A. 1991. Measurement of preferential flow beneath mature corn. Preferential Flow: Proceedings of the National Symposium. American Society of Agricultural Engineers, St. Joesph, MI.

Appendix C: The Estimation of the Number of Infiltrometer Measurements for Assessing Rain Gardens

C.1. Introduction

The accurate estimation of the saturated hydraulic conductivity (K_{sat}) of rain gardens is necessary for the assessment of its proper function and to indicate when maintenance may be necessary or when the overall function is failing. Conducting the level 2 capacity tests requires the measurement of K_{sat} at several locations within the rain garden. Through this research the necessary number of measurements to obtain an accurate mean for the entire rain garden was determined for each rain garden. As expected the K_{sat} data did not follow a normal distribution, therefore before determining the required number of measurements the appropriate transformation need to be applied to the data. The tools and techniques used to determine the distribution of the K_{sat} data for each rain garden will be discussed. The results of the required number of measurements to accurately represent the overall K_{sat} of the rain garden for various level of confidence has been determined and will be given.

C.2. Determination of K_{sat} distribution

Statistical analysis were performed on the measure K_{sat} values to determine what type of distribution best fit the data. K_{sat} data is typically not normally distributed and is often described by a log normal distribution (Tsegaye et al., 1998; Regalado and Muñoz-Carpena, 2004; Jang and Liu, 2004; Bjerg et al., 1992 and Vauclin et al., 1994). The descriptive statistics mean, median, standard deviation (SD), coefficient of variation (CV), skewness, and kurtosis of K_{sat} for each rain garden was computed (Table C.1). Graphs of the cumulative distribution of the measured K_{sat} values along with the theoretical normal and log normal distributions for the data's mean and standard deviation were plotted and visually evaluated to determine the best fit. Figure C.1 through C.8 are the cumulative distribution plots for each rain garden. The visual inspection of the cumulative distribution plots along with the computed CV, skewness, and kurtosis values were used to determine the appropriate distribution for the measured K_{sat} values. Possible outliers were not removed due to the highly heterogeneous soil expected in vegetative landscapes and the uncertainty involved with such removal of data points. Based on the combination of statistical tools utilized, it was determined that a lognormal distribution fit the data best.

Table C.1. Statistical parameters used to determine distribution of K_{sat} of rain gardens.

Statistical Parameters	Burnsville	Cottage Grove	RWMWD (1)	RWMWD (4)
Mean (cm/s)	0.01777	0.02375	0.00748	0.00317
Median (cm/s)	0.01293	0.01958	0.00535	0.00401
SD (cm/s)	0.01782	0.01364	0.00707	0.00214
CV (%)	100.2	57.4	94.6	67.4
Skewness	2.29	0.91	1.84	-1.84
Kurtosis	6.72	0.16	3.59	3.50
	RWMWD (5)	**Thompson Lake**	**U of M, Duluth**	**U of M, St. Paul**
Mean (cm/s)	0.00329	0.01208	0.00906	0.00428
Median (cm/s)	0.00081	0.00531	0.00159	0.00288
SD (cm/s)	0.00486	0.01484	0.01612	0.00375
CV (%)	147.5	122.8	177.9	87.7
Skewness	1.78	1.58	2.40	1.31
Kurtosis	2.24	1.90	5.37	1.21

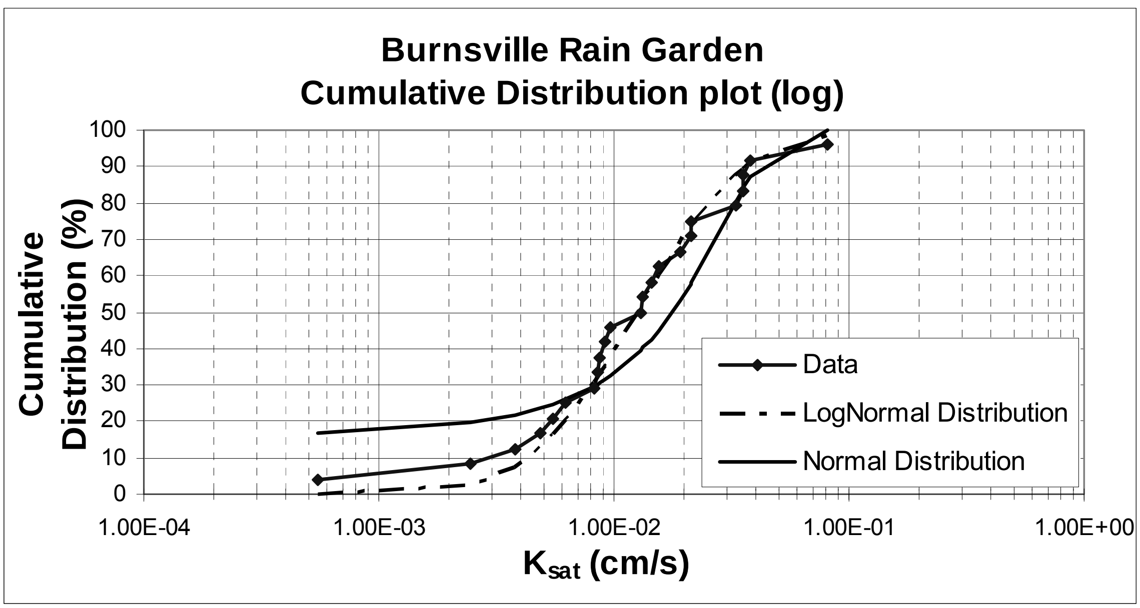

Figure C.1. Burnsville rain garden K_{sat} distribution plot.

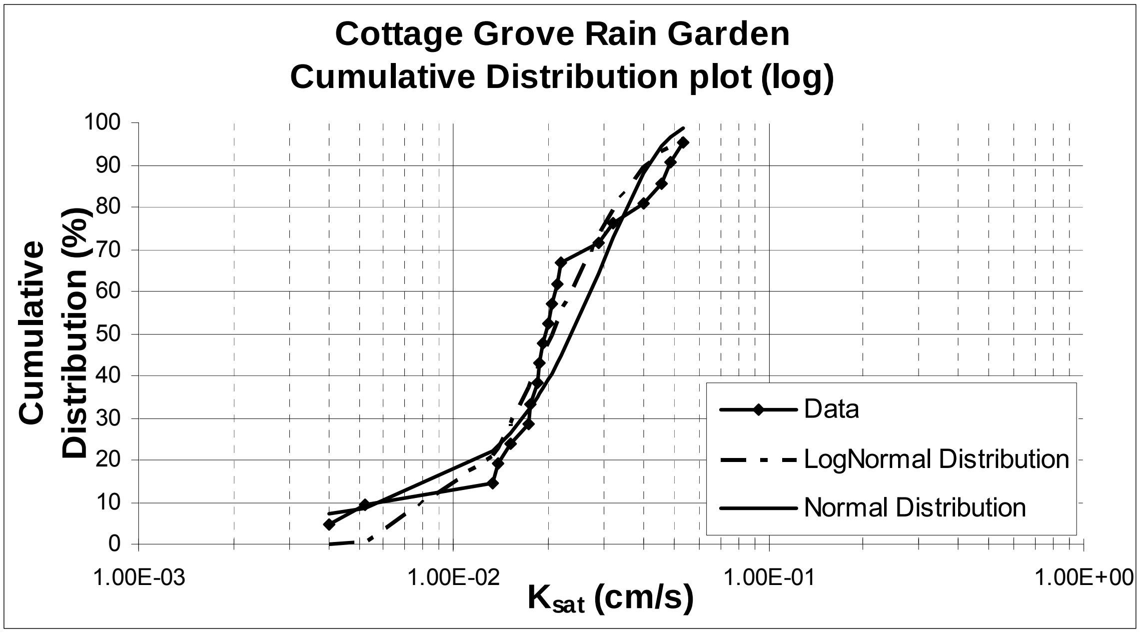

Figure C.2. Cottage Grove rain garden K_{sat} distribution plot.

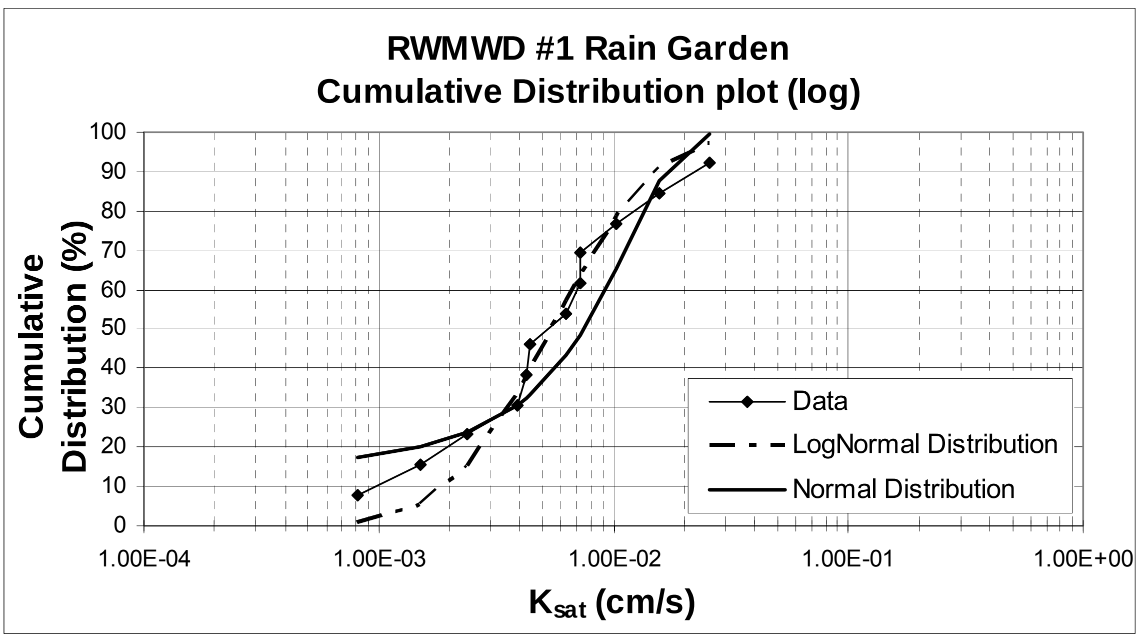

Figure C.3. RWMWD #1 rain garden K_{sat} distribution plot.

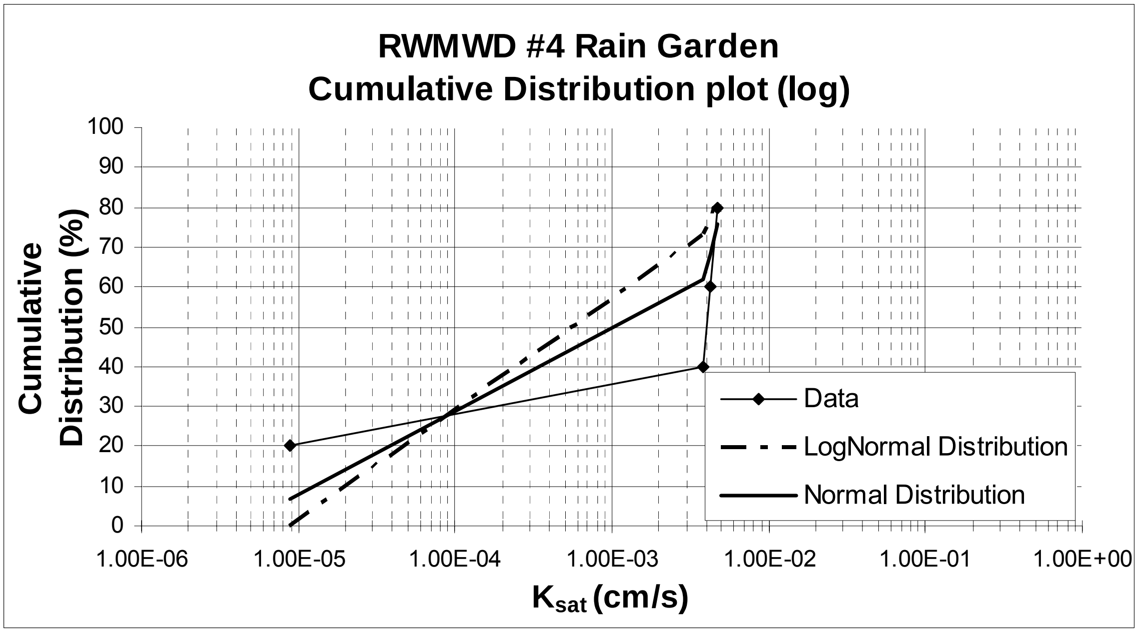

Figure C.4. RWMWD #4 rain garden K_{sat} distribution plot.

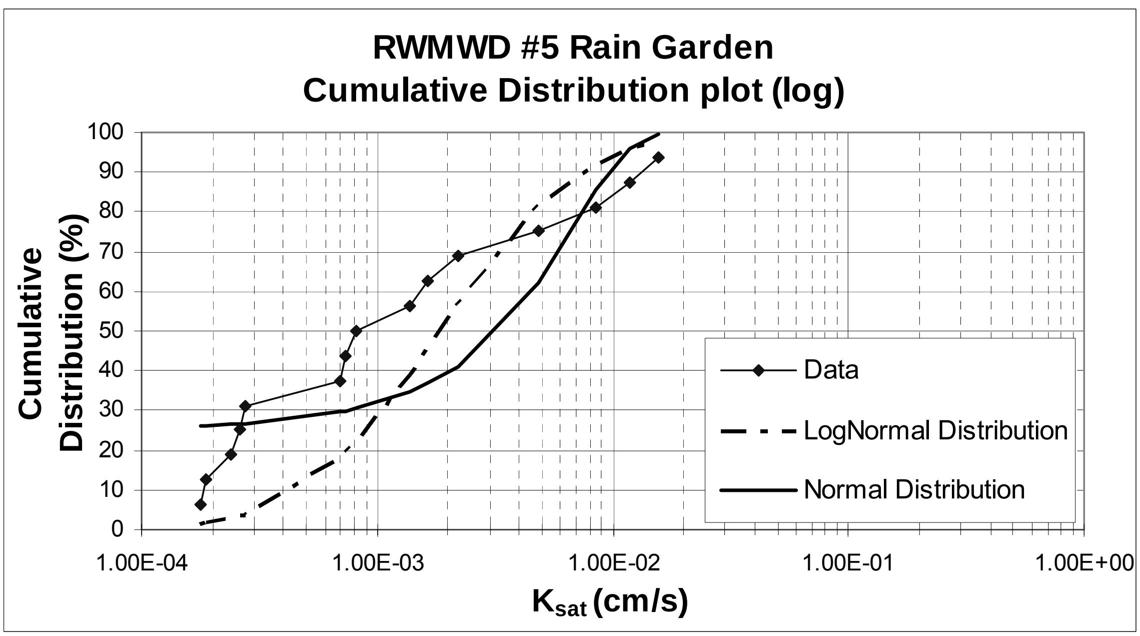

Figure C.5. RWMWD #5 rain garden K_{sat} distribution plot.

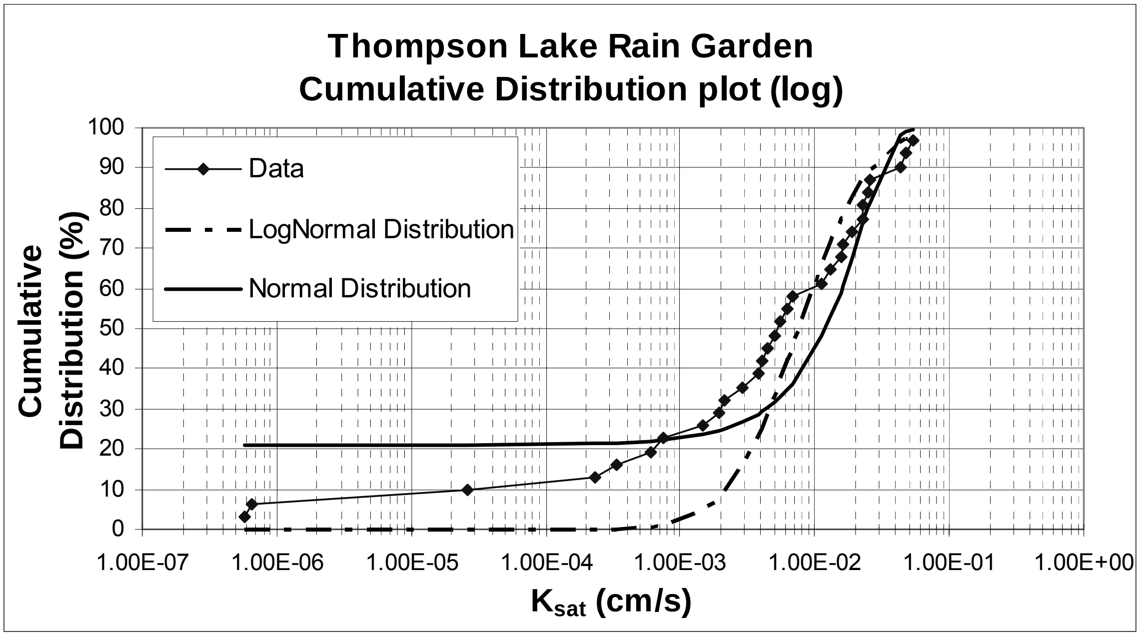

Figure C.6. Thompson Lake rain garden K_{sat} distribution plot.

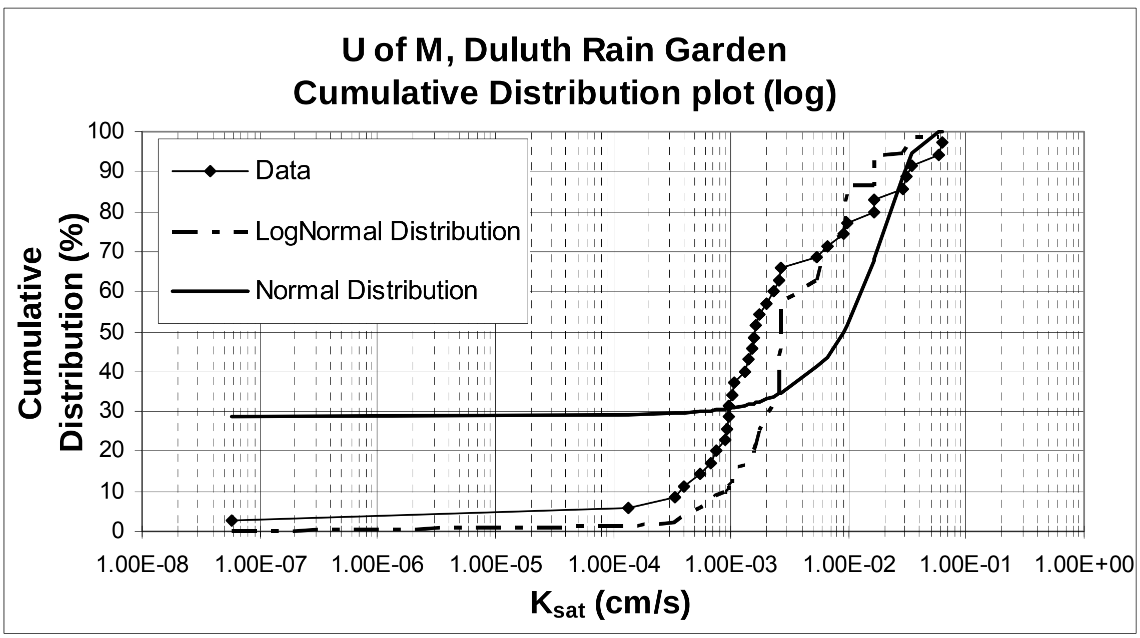

Figure C.7. U of M - Duluth rain garden K_{sat} distribution plot.

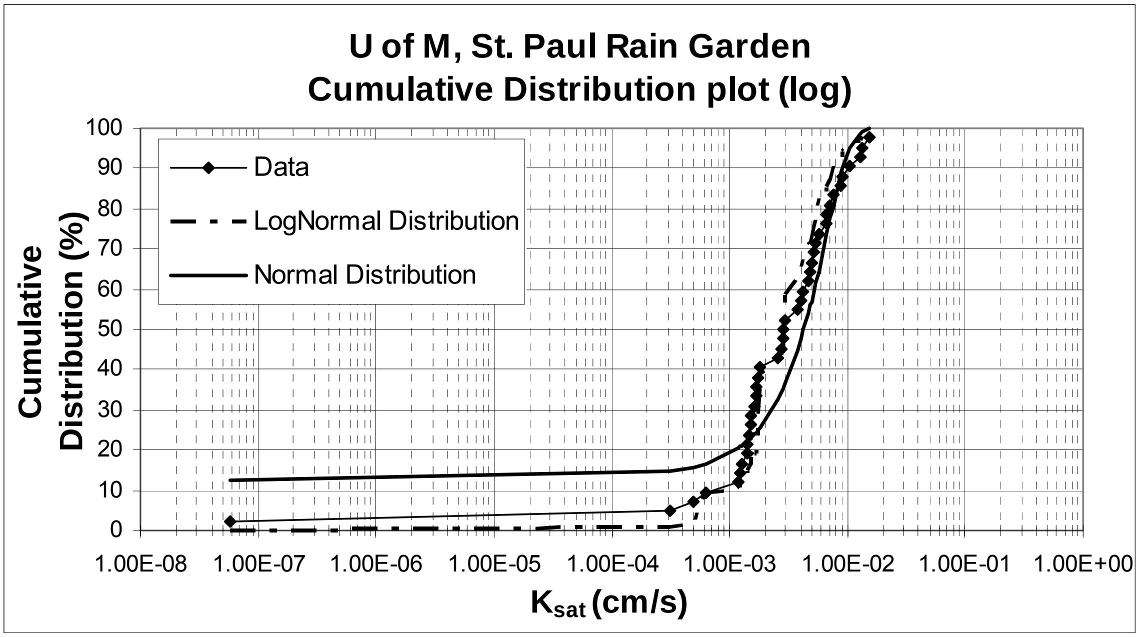

Figure C.8. U of M - St. Paul rain garden K_{sat} distribution plot.

C.3. Estimation of the number of measurements

The number of measurements required to accurately estimate the true mean of the K_{sat} was calculated using Equation 1 where n is the estimated number of measurements required to be within specified range of the mean (C.I. – μ), and z is the tabulated $z_{\alpha/2}$ value for the desired confidence level of estimation.

$$n = \left(\frac{SD * z_{\alpha/2}}{C.I. - \mu} \right)^2$$ **Equation C.1**

The estimation of the number of measurements (n) which would be necessary to obtain an accurate mean value for each rain garden was calculated for a 95%, 85%, and 75% confidence interval. In addition to varying the confidence level, various specified ranges of the mean were also computed. The results of these calculations for each rain garden are shown in Tables C.2, C.3, and C.4.

Table C.2. Estimated number of measurements required to obtain the true mean that is within ±5%, 10%, and 15% of the true mean 95% of the time.

Rain Garden	**N**	**5%**	**10%**	**15%**
Burnsville	**24**	56	14	6
Cottage Grove	**20**	29	7	3
RWMWD (1)	**12**	45	11	5
RWMWD (4)	**4**	16	4	2
RWMWD (5)	**16**	45	11	5
Thompson Lake	**30**	59	15	7
U of M, Duluth	**34**	74	19	8
U of M, St. Paul	**41**	26	6	3

Table C.3. Estimated number of measurements required to obtain the true mean that is within ±5%, 10%, and 15% of the true mean 85% of the time.

Rain Garden	**N**	**5%**	**10%**	**15%**
Burnsville	**24**	30	8	3
Cottage Grove	**20**	16	4	2
RWMWD (1)	**12**	24	6	3
RWMWD (4)	**4**	9	2	1
RWMWD (5)	**16**	24	6	3
Thompson Lake	**30**	32	8	4
U of M, Duluth	**34**	40	10	5
U of M, St. Paul	**41**	14	4	2

Table C.4. Estimated number of measurements required to obtain the true mean that is within ±5%, 10%, and 15% of the true mean 75% of the time.

Rain Garden	**N**	**5%**	**10%**	**15%**
Burnsville	**24**	19	8	2
Cottage Grove	**20**	10	3	1
RWMWD (1)	**12**	15	4	2
RWMWD (4)	**4**	6	1	1
RWMWD (5)	**16**	15	4	2
Thompson Lake	**30**	20	5	2
U of M, Duluth	**34**	26	6	3
U of M, St. Paul	**41**	9	2	1

C.2. References

Bjerg, P. L., K. Hinsby, T. H. Christensen, and P. Gravesen. 1992. "Spatial variability of hydraulic conductivity of an unconfined sandy aquifer determined by a mini slug test." *Journal of Hydrology*, 136(1-4), 107-122.

Jang, Chen-Shin, and Chen-Wuing Liu. 2004. "Geostatistical analysis and conditional simulation for estimating the spatial variability of hydraulic conductivity in the Choushui River alluvial fan, Taiwan." *Hydrological Processes*, 18, 1333-1350.

Regalado, C. M., and R. Munoz-Carpena. 2004. "Estimating the saturated hydraulic conductivity in a spatially variable soil with different permeameters: a stochastic Kozeny-Carman relation." *Soil and Tillage Research*, 77(2), 189-202.

Tsegaye, T., Robert L. Hill. 1998. "Intensive tillage effects on spatial variability of soil physical properties." *Soil Science*, 163(2), 143-154.

Vauclin, M., D. E. Elrick, J. L. Thony, G. Vachaud, P. Revol, and P. Ruelle. 1994. "Hydraulic conductivity measurements of the spatial variability of a loamy soil." *Soil Technology*, 7(3), 181-195.

Appendix D: The Construction and Use of the Modified Philip-Dunne Infiltrometer

D.1. Selection of field permeameters and infiltrometers

There are several devices that can be used to make measurements of the soil's saturated hydraulic conductivity in the field. Some of the devices available include the air-entry permeameter, Guelph permeameter, tension infiltrometer, double and single ring infiltrometers, disk infiltrometer, and the Modified Philip-Dunne infiltrometer. Several of these devices have been evaluated based on specific criteria; see table D.1 for a summary. Table D.1 demonstrates that the Modified Philip-Dunne infiltrometer has an advantage over the other devices in several of the criteria, making it one of the simplest and most efficient devices for use in the field. Based on the evaluation of the devices, the Modified Philip-Dunne infiltrometer is recommended for estimating saturated hydraulic conductivity in the field.

Table D.1. Comparison of infiltrometers and permeameters.

CRITERIA	Double Ring Infiltrometer	Modified Philip-Dunne Infiltrometer	Minidisk Infiltrometer	Guelph Permeameter	Tension Infiltrometer
Transportability of equipment	2	1	1	2	3
Volume of water needed	3	1	1	2	3
Experiment duration	3	2	1	3	2
Simplicity of operation	2	1	2	3	3
Cost	2	1	1	3	3
Personnel requirements	1	1	1	2	2
Accuracy	1	1	2	1*	2*

Criteria evaluation: 1 = most desired, 2 = second-most desired, 3 = least desired

** Device accuracy evaluation based on literature.*

D.2. Constructing a Modified Philip-Dunne infiltrometer

The Modified Philip-Dunne infiltrometer is a open-ended cylinder which should have a maximum height of approximately 60 cm, a minimum height of 30 cm, and a diameter of 10 cm or greater. Any rigid material for cylinder maybe used, however, it was found that thin-walled aluminum pipe worked well making the infiltrometer light-weight and durable. It may also be helpful to bevel the bottom of the cylinder to ease insertion into the soil if a thicker-walled material is being used. Next, connect a transparent piezometer tube to the cylinder with a small elbow joint about 5 cm from the bottom and on the outside of the device from which to make visual readings. Measuring tape for making height measurements of water inside the piezometer tube should be positioned parallel and next to the tube with zero starting at the piezometer elbow joint. For ease of identification, it is recommended to mark the height at which the water level will be at the maximum height (h_0) on the infiltrometer. Finally mark around the outside of the cylinder at the base of the piezometer elbow to indicate the depth that the cylinder should be inserted into the soil. Figure D.1 is an example of a Modified Philip-Dunne infiltrometer.

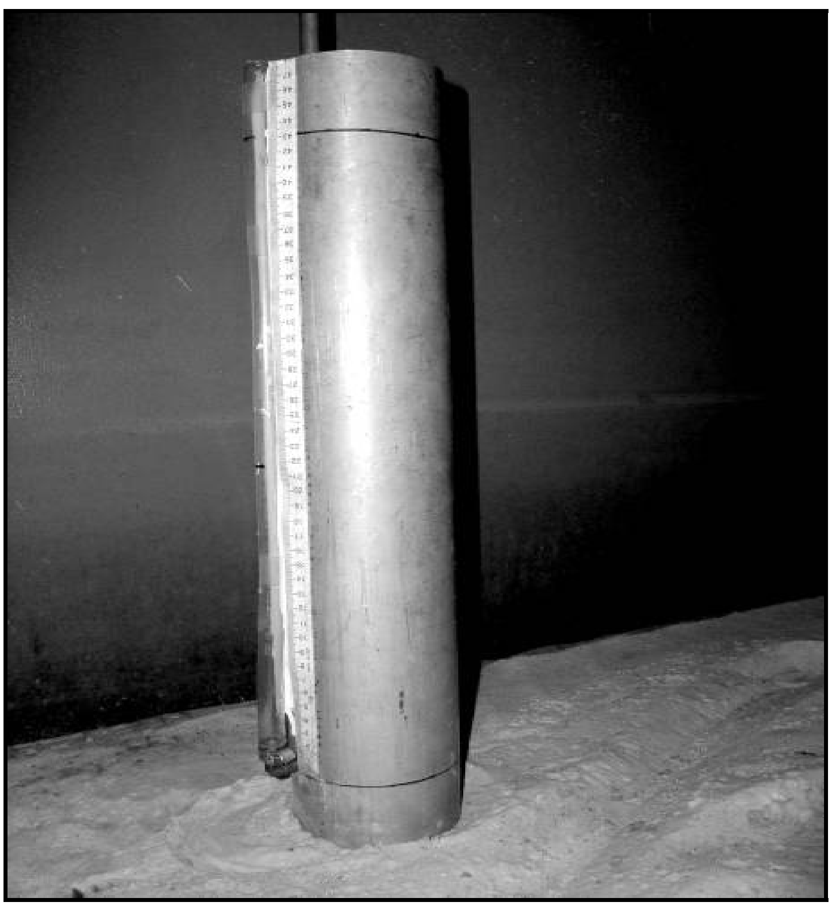

Figure D.1. Photograph of the Modified Philip-Dunne infiltrometer.

D.3. Field procedure for Modified Philip-Dunne infiltrometer

1. Determine the number of testing locations required by using the estimated variance of the saturated hydraulic conductivity of the soil within the specific stormwater BMP. Several bioretention practices (rain gardens) in the North Central USA have been evaluated for variance of saturated hydraulic conductivity to approximate the number of locations necessary to obtain an accurate representation of the entire rain garden. For a site specific estimate the variance and mean of the saturated hydraulic conductivity must first be estimated by making several measurements. Once an estimate of the mean and variance are obtained equation D.1 can be used to calculate the appropriate number of locations required for a representative saturated hydraulic conductivity value.

$$n = \left(\frac{SD * z_{\alpha/2}}{C.I. - \mu} \right)^2 \qquad \textbf{Equation D.1}$$

   Where n is the estimated number of measurements required to be within a specified range of the mean (C.I. – μ), and z is the tabulated $z_{\alpha/2}$ value for the desired confidence level of estimation.

   To obtain a general estimate for the number of measurements required that is not based on a site specific mean and variance figureD.2 may be used as a starting point. The figure is based on data compiled from several different rain garden sites in north central USA. Select the range about the mean value and confidence interval based on the level of accuracy desired, and then refer to figure D.2 to determine the number of measurements to begin with, and then estimate for the number of tests required based on specific infiltrometer tests conducted.

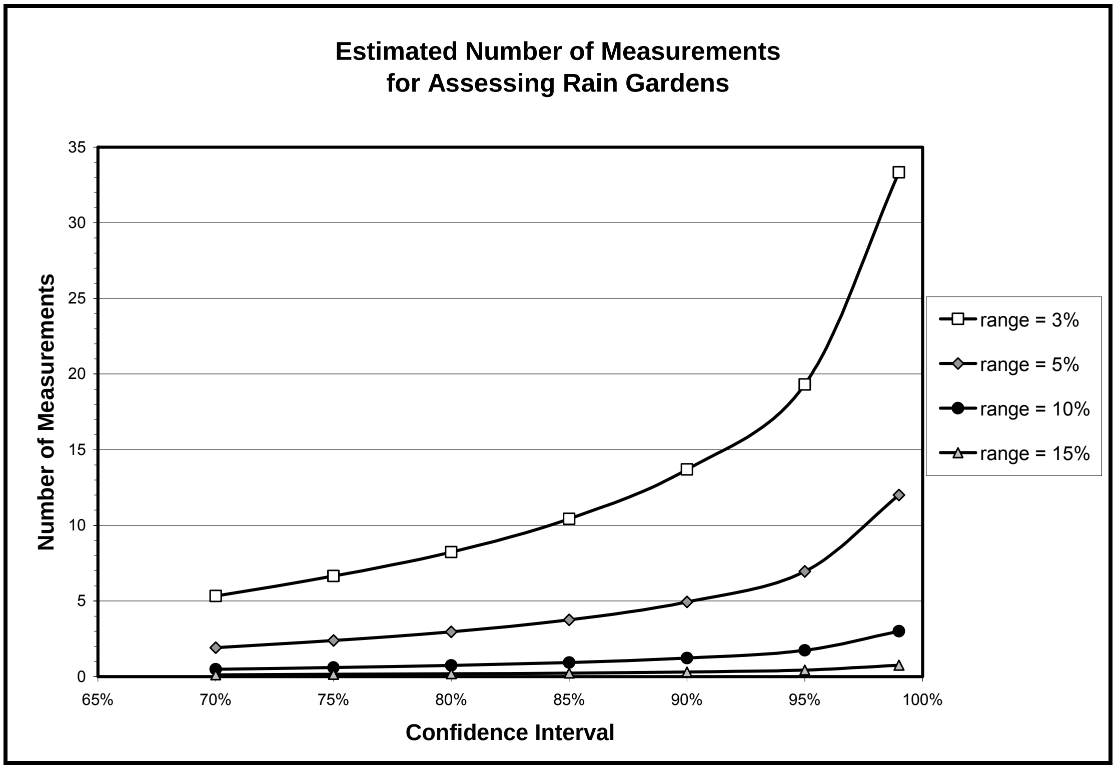

Figure D.2. Estimated number of measurements for all rain gardens.

1. Randomly select the locations throughout the stormwater BMP where the point measurements are to be performed. Ideally point measurements should be evenly distributed throughout the site. It may also be advantageous to record the location of each point measurement with a hand-drawn map or GPS if additional assessments will be performed at the site in the future.

2. At a point measurement location, pound the device uniformly into the ground to a depth of approximately 5 cm, making sure not to pound the piezometer tube opening below the surface. Ensure that the soil around the base of the Modified Philip-Dunne infiltrometer is pressed firmly against the device to prevent seepage.

3. Directly around the base of the Modified Philip-Dunne infiltrometer, an initial volumetric soil moisture measurement must be made. Suggested moisture measurement techniques include the gravimetric method (and using dry bulk density to convert it to volumetric moisture) or using a portable soil moisture sensor such as a ThetaProbe®. Refer to Methods of Soil Analysis, Part 1 (Klute, 1986) or ASTM Test Methods D2216/D4643 for a more detailed procedure on measuring soil moisture using the gravimetric method.

4. Once the initial soil moisture measurement has been made, the Modified Philip-Dunne infiltrometer can be filled with water. To prevent scouring of the soil surface, hay or some other porous material may be placed at the bottom of the device. When

the water level reaches the marked initial height (h_0), stop filling the device and begin the timer.

5. Either periodically or at a regular time interval record the time since the test began and corresponding height of water while the water drains from the device until the device empties and the test is complete.

6. After all the time vs. height measurements have been recorded and the device is empty, remove the Modified Philip-Dunne infiltrometer and take the final soil moisture measurement as soon as possible from where the device was positioned. Repeat steps 3 through 7 at all of the pre-determined test locations within the stormwater BMP.

D.4. Data analysis for Modified Philip-Dunne infiltrometer

The original Philip-Dunne infiltrometer technique involves creating a borehole in which the device is placed. This infiltrometer was modified to incorporate surface infiltration and capture any effects of sediment accumulation in the stormwater BMP. Due to modifications in this technique the analysis for determining saturated hydraulic conductivity needed to be altered accordingly. This alteration included changing the geometry of the wetted bulb from a sphere to spherical cap and accounting for one-dimensional flow through the soil contained within the bottom of the device. The radius of the spherical source, r_0, is then given by equation D.2 where r_1 is the radius of the device.

$$r_0 = \frac{r_1}{\sqrt{2}}$$ **Equation D.2**

By applying these alterations to the original analysis completed by J.R. Philip (1993) equations D.3 and D.4 are obtained.

$$\Delta P = \frac{\pi^2}{8}\left[\frac{(\theta_f - \theta_i)\left(R^2 + RL_{\max}\right)}{-\bar{K}}\frac{dR}{dt} - 2r_0^{\,2}\right] \times \frac{\ln\left[R\left(r_0 + L_{\max}\right)/r_0\left(R + L_{\max}\right)\right]}{L_{\max}}$$ **Equation D.3**

$$\Delta P = C - h(t) - L_{\max} - \frac{qL_{\max}}{K}$$ **Equation D.4**

Where ΔP is the change in pressure from the source to the wetting front, L_{max} is the distance the device is inserted into the ground, θ_f and θ_i are the final and initial moisture contents, respectively, $h(t)$ is the height of water at time t, K is the mean saturated hydraulic conductivity, and C is the capillary pressure. The radial distance to the sharp wetting front, R, can be found by finding the solution to equation D.5.

$$\frac{(H_0 - h)r_1^{\,2}}{\Delta\theta} = \frac{2R^3 - 3R^2 L_{\max} - L_{\max}^{\;3} - 2r_0^{\;3}}{3}$$ **Equation D.5**

The derivative of *R* with respect to time, *dR/dt*, may be estimated by taking a finite difference of *R* versus time. Equations D.3 and D.4 apply after the test has reached the point where R(t) is greater than the radial distance from bottom center of the device to the edge of the device at the soil surface. Lastly the remaining unknown variables are *K* and *C*, which can be found by setting the right sides of equations D.3 and D.4 equal to one another and finding the best fitting solution by varying *K* and *C*. To aid in this analysis a Microsoft Excel® spreadsheet with instructions for use is provided via the internet for download at the following link: http://wrc.umn.edu/outreach/stormwater/bmpassessment/linksandresources.html.

Once the saturated hydraulic conductivity has been calculated for all the locations within the stormwater BMP, the results must be averaged using the arithmetic mean to obtain the overall value. As a conservative estimate, saturated hydraulic conductivity can be considered equal to the infiltration rate.

To determine if the stormwater BMP is able to infiltrate a certain runoff volume within the required 48 hour time period use the following calculations:

1. Saturated hydraulic conductivity multiplied by the surface area to obtain a conservative estimate of the infiltration rate (volume per time), and
2. Runoff volume divided by the infiltration rate to estimate the time required to infiltrate the selected runoff volume. Example D.1 will illustrate this procedure more fully.

Example D.1

A rain garden with a surface area of 3000 ft^2 (279 m^2), a ponding depth of 0.667 ft (0.20 m), and an estimated conservative infiltration rate of 1.6 in/hr (0.041 m/hr) is to be assessed for total time to infiltrate water at it storage capacity. Determine the storage capacity and the time required to infiltrate water.

Solution:

Determine the storage capacity.

$$\text{Storage capacity} = 0.667 \text{ ft x } 3000 \text{ ft}^2 = 2000 \text{ ft}^3$$

Determine the overall infiltration rate of the rain garden.

$$\text{Overall Infiltration Rate} = 0.133 \text{ ft/hr x } 3000 \text{ ft}^2 = 400 \text{ ft}^3\text{/hr}$$

Determine the total time required to infiltrate the water in the rain garden at capacity.

$$\text{Storage capacity/Infiltration rate} = \text{total time}$$

$$\text{Total time to empty} = 2000 \text{ ft}^3 / 400 \text{ ft}^3\text{/hr} = 5 \text{ hr}$$

D.5. References

A.S.T.M. D2216-05, 2005. Standard Test Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass. ASTM International, Editor.

A.S.T.M. D 4643-00, 2000. Standard Test Method for Determination of Water (Moisture) Content of Soil by the Microwave Oven Method. ASTM International, Editor.

Klute, A. 1986. Methods of Soil Ananlysis, Part I. Physical and Mineralogical Methods, 2nd edition. Soil Science Society of America, Inc. Publisher, Madison, WI.

Munoz-Carpena, R., C. M. Regalado, J. Alvarez-Benedi, and F. Bartoli. 2002. Field evaluation of the new Philip-Dunne permeameter for measuring saturated hydraulic conductivity. Soil Science 167:9-24.

Philip, J. R. 1993. Approximate Analysis of Falling-Head Lined Borehole Permeameter. Water Resources Research 29:3763-3768.

Appendix E: Standard Procedure for Level 1 Assessment: Visual Inspection

E.1. Standard Operating Procedures for Biologically Enhanced Practices (including Bioretention, Constructed Wetlands, Swales, and Filter Strips)

1. Certified Reference:

1.1. None.

2. Application:

2.1. This method is applicable to biologically enhanced practices as defined in Chapter 11, Biologically Enhanced Systems of the *Assessment of Stormwater Best Management Practices Manual*.

3. Summary of Method:

3.1. This standard protocol is used as a basis for the visual inspection of biologically enhanced practices. The questions in section 8.4 below are answered from visual observations of the site and documented with a photographic or video-graphic camera.

4. Interferences:

2.1. Visual inspection requires adequate weather conditions. Fog or other visually limiting weather condition can result in an inaccurate or incomplete visual inspection. Such weather conditions should be avoided whenever possible.

5. Apparatus:

5.1. Camera (digital or film, video or photographic)

6. Materials:

6.1. Field Data Sheet (see attached).

7. Safety:

7.1. This procedure requires field inspection of the site and photographic or video graphic documentation. Caution and appropriate use of safety equipment and traffic controls should be used when walking around and in stormwater BMPs to avoid personal injury.

8. Procedure:

8.1. Print out this Standard Protocol for the visual inspection of biologically enhanced practices.

8.2. Obtain apparatuses and materials as outlined in sections 5 and 6 above.

8.3. Travel to the biologically enhanced practice that will be assessed by visual inspection.

8.4. Fill out the attached Field Data Sheet (see below).

9. Calculations:

9.1. None required. See Chapter 12 of *Assessment of Stormwater Best Management Practices Manual.*

10. Quality Control:

10.1. Photographic documentation for the questions answered above (section 8.4) must be provided with this protocol.

11. Additional References:

11.1. None.

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Assessment Project

E.2. Field Data Sheet for Level 1 Assessment: Visual Inspection

Bioretention Practices (including Rain Gardens)

Inspector's Name (s): ____

Date of Inspection: ____

Location of the Bioretention Practice

  Address or Intersection: ____________________________________

  Latitude, Longitude: ______________________________________

Date the rain garden began operation: __________________________

Size of the rain garden (ft^2): _________________________________

Time since last rainfall (hr): ____________________________________

Quantity of last rainfall (inches): ______________________________

Rainfall Measurement Location: ___________________________

Site Sketch

Based on visual assessment of the site, answer the following questions and make photographic or video-graphic documentation:

1) Has visual inspection been conducted on this location before?

☐ Yes ☐ No ☐ I don't know

1.a) If yes, when? ____

1.b) Based on previous visual inspections, have any corrective actions been taken?

☐ Yes ☐ No ☐ I don't know

1.c) If yes, describe action taken and date of action.

____
____
____
____

2) Has it rained within that last 48 hours at this location?

☐ Yes ☐ No ☐ I don't know

3) Does this bioretention practice utilize any pretreatment practices upstream?

☐ Yes ☐ No ☐ I don't know

3.a) If yes, please describe.

____
____
____
____

4) Are there multiple inlet structures?

☐ Yes ☐ No

4.a) If yes, how many inlets are present?

2 3 4 5 6 or more

4.b) Are any of the inlet structures clogged?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
No					
Partially					
Completely					
Not Applicable					

4.c) If yes, what with?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Debris					
Sediment					
Vegetation					
Other					

If Other: ____

If Other: ____

If Other: ____

If Other: ____

If Other: ____

5) Is the inlet or outlet structure askew or misaligned?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Yes					
No					

5.a) If yes, why?

	Inlet 1	Inlet 2	Inlet 3	Inlet 4	Inlet 5
Ice/Frost Heave					
I don't know					
Other					

If Other: ____

If Other: ____

If Other: ____

If Other: ____

If Other: ____

6) Is there standing water in the bioretention practice?

☐ Yes ☐ No

6.a) If yes, does the water have:

Surface sheen (from oils/gasoline)

Murky color (from suspended solids)

Green color (from algae or other biological activity)

Other: ____

7) Is there evidence of illicit storm sewer discharges?

☐ Yes ☐ No

7.a) If yes, please describe: ____________________________________

____

____

____

8) Does the bioretention practice smell like gasoline or oil?

☐ Yes ☐ No

9) Is there vegetation in the bottom of the bioretention practice?

☐ Yes ☐ No

9.a) What is the approximate vegetation cover

☐ 0 – 25% ☐ 25 – 50% ☐ 50 – 75% ☐ 75 –100%

10) Does the current vegetation match the design plan?

☐ Yes ☐ No

10.a) Is there the presence of:

☐ Weeds

☐ Wetland vegetation

☐ Invasive vegetation

☐ None of the above

11) Does the vegetation appear to be healthy?

☐ Yes ☐ No

11.a) If no, please describe: ___________________________________

____

____

____

12) Is the vegetation the appropriate density/size?

☐ Yes ☐ No

12.a) If no, please describe:

____
____
____
____

13) What is the USDA texture of the soil profile and soil color in the basin?

Depth: _____ Texture: __________ Color: _____
Depth: _____ Texture: __________ Color: _____
Depth: _____ Texture: __________ Color: _____
Depth: _____ Texture: __________ Color: _____

14) Does the soil appear to be saturated?

☐ Yes ☐ No

15) Are there indications of any of the following in the bottom of the bioretention practice?

☐ Sediment deposition

☐ Erosion or channelization

☐ Excessive vegetation (that needs mowing or removal)

litter, large debris, solid waste

☐ Other: ____

☐ None of the above

15.a) If sediment deposition is evident, what is the source?

☐ Erosion or channelization inside the practice

☐ Erosion or channelization outside the practice

☐ Construction site erosion

☐ Other: ____

☐ I don't know

16) Does the soil of the bioretention practice appear to be compacted?

☐ Yes ☐ No

16.a) If yes, what is the bulk density of the soil: ___________________

17) Is the bottom of the bioretention practice covered with a layer of silts and/or clays?

☐ Yes ☐ No

18) Are there indications of any of the following on the banks of the bioretention practice?

☐ Erosion or channelization

Other: ____

☐ No

19) Is the overflow or bypass structure clogged, partially or completely?

☐ No ☐ Partially ☐ Completely ☐ Not Applicable

19.a) If yes, what with?

☐ Debris

Sediment

☐ Vegetation

☐ Other: ____

20) Is the overflow or bypass structure askew or misaligned?

☐ Yes ☐ No

20.a) If yes, why?

☐ I don't know

☐ Ice/Frost heave

☐ Other: ____

Other observations:

____

____

____

Inspector's Recommendations:

21) When is maintenance needed?

- ☐ 5 – Before the next rainfall
- ☐ 4 – Before the next rainy season
- ☐ 3 – Possibly after the next season
- ☐ 2 – Within a year or two
- ☐ 1 – No sign that any will be required

Additional Comments:

____

____

____

____

E.3. Troubleshooting Failure: Visual Inspection

Bioretention Practices

The following sections provide discussion about each question answered on the field data sheet above.

1) Has visual inspection been conducted on this location before?

It is important to determine whether this location has been previously assessed so that assessment efforts are cost effective (i.e., neither duplicated nor wasted). If previous assessment has occurred, the current assessment should verify that actions suggested by the previous assessment were completed and are effective.

2) Has it rained within that last 48 hours at this location?

Many bioretention practices are designed to drain the design storm volume (i.e., water quality volume, maximum storage volume) within 48 hours (Minnesota Stormwater Steering Committee 2005). Assessment within 48 hours of a rainfall event may provide performance clues. Additionally, rainfall within the last 48 hours at a location will alter the interpretation of answers to other questions.

3) Does this bioretention practice utilize any pretreatment practices upstream?

Pretreatment practices are required by the MPCA in some MS4 construction permits for bioretention practices. If this practice does not have any pretreatment upstream, it may be in violation of this code.

4) Are any of the inlet structures clogged?

Inlet structures should be free of any debris, sediment, vegetation, and other obstructions so that stormwater runoff can easily enter the bioretention practice. If an inlet structure is even partially clogged, suspended solids may be deposited in the upstream conveyance system or upstream areas may flood because the conveyance systems are limited by such obstructions. Any obstructions should be removed immediately to ensure proper operation of the bioretention practice.

5) Are any of the inlet structures askew or misaligned?

Misaligned inlet structures often allow stormwater runoff to enter or exit a bioretention practice by means other than those intended by design or prevent stormwater runoff from entering the practice at all. This condition can result in erosion, channelization, or flooding of surrounding areas, which can further exacerbate the misalignment or create other problems.

Inlet structures can become misaligned for several reasons, including frost heave of the soil, vehicular collision, and geotechnical failure. Misaligned inlet structures should be repaired or replaced as soon as possible to reduce detrimental impact. Any obstructions should be removed immediately to ensure proper operation of the infiltration practice.

6) Is there standing water in the bioretention practice?

Standing water in a bioretention practice is the result of one of three possibilities: (1) rainfall has occurred recently such that stormwater runoff has not had 48 hours to pass infiltrate, (2) the infiltration rate of the bioretention practice is slow such that stormwater runoff does not pass through the bioretention practice within 48 hours, but does pass through the bioretention practice given enough time, or (3) the soil media is clogged and does not allow any stormwater runoff to infiltrate. If it has rained in the last 48 hours (Question 2), then the bioretention practice may be functioning properly and requires additional assessment (level 2 or higher) to determine whether the soil media is clogged. If, however, it has not rained in the last 48 hours, it is likely that the bioretention practice is either option (2) or (3).

Surface sheen is caused by hydrocarbon substances such as automotive oil or gasoline and may indicate illicit discharges. If hydrocarbons are proven to not be illegally discharged into the bioretention practice, then a surface sheen may indicate that stormwater runoff is stored in the bioretention practice such that the small amounts of hydrocarbons typically found in stormwater runoff are accumulating. If this is happening, then the bioretention practice is failing. There are several illicit discharge manuals available for identifying, locating, and eliminating illicit discharges (e.g., Brown et al. 2004).

Stormwater runoff with a murky color is evidence of a large suspended solids concentration that is most likely made up of fine particle sizes such as clays and silts because sand particles settle out of standing water very rapidly (as discussed in Chapter 10: Sedimentation in the *Assessment of Stormwater Best Management Practices Manual*). Stormwater runoff with a murky color can indicate that the watershed is a significant source of fine particle suspended solids which can quickly clog a bioretention practice. Murky stormwater runoff in a bioretention practice may indicate that stormwater runoff has recently entered the bioretention practice such that fine particles have not had time to settle out.

Stormwater runoff with a green color from algae has been stored in the bioretention practice for a long period of time such that microorganisms have developed. Stormwater runoff is not passing though the bioretention practice properly and therefore the practice is failing.

7) Is there evidence of illicit storm sewer discharges?*)*

An illicit discharge manual (e.g., Brown et al. 2004) should be consulted for identifying and locating illicit stormwater discharges.

8) Does the bioretention practice smell like gasoline or oil?

If a bioretention practice smells like gasoline or oil it is possible that hydrocarbon substances such as automotive oil or gasoline are being illicitly discharged into the practice or upstream in the watershed. If hydrocarbons are proven to not be illegally discharged into the bioretention practice, then an oil/gasoline smell may indicate that stormwater runoff is stored in the bioretention practice such that the small amounts of hydrocarbons typically found in stormwater runoff are accumulating. For more information on identifying, locating, and eliminating illicit discharges, refer to a manual such as Brown et. al. (2004).

9) Is there vegetation in the bottom of the bioretention practice?

Vegetation in the bottom of a bioretention practice is designed to dry out the soil in between storms and to maintain the infiltration effectiveness. Plants can lose 30% of their root structures annually which produces macropores. Macropores in a bioretention practice can increase the infiltration rate of the practice so that more stormwater runoff is infiltrated. Additionally, vegetation can reduce overland flow velocities and can therefore reduce erosion and re-suspension of captured solids.

Vegetation can also be an indication of the drain time of a bioretention practice. Terrestrial vegetation often cannot withstand long periods of inundation and some cannot withstand short periods of inundation. If a bioretention practice has an abundance of terrestrial vegetation, it is likely that the practice infiltrates stormwater runoff quickly (< 48 hours) and is therefore operating properly. If, however, the bioretention practice has signs of aquatic vegetation or has little vegetation, it is likely the practice is not infiltrating stormwater runoff at all and is therefore failing.

10) Does the current vegetation match the design plan?

Species of vegetation in planting plans for bioretention practices are selected based on desirable characteristics that a particular species of plant may exhibit. During the construction and throughout the operational life of a bioretention practice the vegetation may deviate from the original design and thus possibly affecting the performance of the bioretention practice. If planting designs are available compare the currently existing vegetation to the vegetation designated in the design plans. Particular things to look for are certain species that are not surviving and/or have disappeared as well as introduction of weeds, wetland vegetation, and/or other invasive vegetation. For guidance on vegetation identification please refer to Plants for Stormwater Design: Species Selection for the Upper Midwest (Schmidt and Shaw, 2003).

11) Does the vegetation appear to be healthy?

The health of vegetation can indicate conditions that may be too wet/dry, too sunny/shady, lack of nutrients, compacted soil, presence of toxic pollutants, ect. The survival of the vegetation is critical to maintain proper function of a bioretention practice. During the growing season assess the apparent visual health of the vegetation in the bioretention practice. Some indications of unfavorable conditions are: wilted leaves/stem, discoloration of leaves, lack of flowering buds developing, stunted growth, and a decrease in the number of plantings present. For guidance on vegetation identification please refer to Plants for Stormwater Design: Species Selection for the Upper Midwest (Schmidt and Shaw, 2003).

12) Is the vegetation the appropriate density/size?

Under optimal site conditions the vegetation should have an appropriate size and density for that particular species. Under development can be an indication of poor health while over development can hinder the development of other species in the bioretention practice. For guidance on vegetation identification please refer to Plants for Stormwater Design: Species Selection for the Upper Midwest (Schmidt and Shaw, 2003).

13) What is the USDA texture of the soil profile and soil color in the basin?

For bioretention practices to function, hydraulic conditions of the soil must be appropriate. Ideally the soil will have a coarser texture to allow for adequate drainage. Soil texture is determined by the distribution of particle sizes which are classified as sand, silt, and clay. The USDA Soil Textural Triangle classifies the soil texture based on the percentage of each particle size class. For a visual inspection of the soil texture it is recommended that the flow chart in figure 11.6 in Chapter 11 of the *Assessment of Stormwater Best Management Practices Manual* be used to classify the soil texture. The texture of subsurface soil layers can influence the hydrology of the bioretention practice and therefore are important to investigate. Color of the soil also aids in the understanding of the subsurface hydrology. When possible use Munsell® Soil Color Charts to accurately determine the soil color.

14) Does the soil appear to be saturated?

More than 48 hours after a storm event surface soils should not be inundated. Soils that are saturated for long periods of time may not be draining properly and creating hydric conditions. Overly dry soils may inhibit plant growth which is essential to the proper performance of bioretention practices.

15) Are there indications of any of the following in the bottom of the bioretention practice?

Sediment deposition may indicate that pretreatment devices have reached sediment storage capacity, are not efficiently removing settable solids, or are not present. Sediment deposition may also indicate a significant source of sediment in the watershed that may require remediation to prevent downstream pollution. Sediment deposition reduces the bioretention practice surface area available for infiltration and therefore can reduce the stormwater runoff volume that is infiltrated.

Erosion or channelization indicates that flow velocities entering, or in, the bioretention practice are large or that stormwater runoff is entering the practice by means other than those intended by design. In either case, stormwater runoff is not stored in the bioretention practice such that significant infiltration in the areas where erosion and channelization are occurring.

Excessive vegetation, especially with deep roots, can increase and maintain infiltration rates in bioretention practices that do not have impermeable surfaces (e.g., concrete). If the surface of the bioretention practices becomes clogged or sealed, vegetation can provide pathways for stormwater runoff to penetrate the surface and subsequently infiltrate into the underlying soils, increasing runoff volume reduction by the bioretention practices. Vegetation in bioretention practices is beneficial and therefore should only be controlled for aesthetic or nuisance reasons.

Litter, large debris, and solid waste in a bioretention practice are indications that pretreatment practices are failing or not present. Litter, large debris, and solid waste may limit the effectiveness of bioretention practice by reducing the surface available for infiltrating stormwater runoff.

16) Does the soil of the bioretention practice appear to be compacted?

Heavily compacted soils can inhibit plant root growth as well as restrict water flow through the soil. Visual indications of compaction include visible bare soil that is smooth and hard. For a more accurate indication of the level of soil compaction it is recommended that the soil bulk density be measured. For the standard procedure to measure bulk density see Methods of Soil Analysis, Part 1 – Physical and Mineralogical Methods (Klute, 1986).

17) Is the bottom of the bioretention practice covered with a layer of silts and/or clays?

A visible layer of silts, clays, or both is a likely indication that the bioretention practice is clogged. Bioretention practices collect particles on the surface and in the pore spaces of the soil. Silts, clays, or both present on the surface of the bioretention practice indicates that the pore spaces within the soil are likely filled, or that stormwater runoff is stored in the basin or trench long enough for these fine particles to settle out or for the stored stormwater runoff to evaporate. The bioretention practice is not likely infiltrating stormwater runoff in less than 48 hours as recommended by design guidelines (Minnesota Stormwater Steering Committee 2005).

18) Are there indications of any of the following on the banks of the bioretention practice?

Erosion or channelization on the banks of a bioretention practice indicates that stormwater runoff is entering at a large velocity by means other than designed. Erosion and channelization on the banks can fill the bioretention practice with sediments from the bank and subsequently reduce the practice's effectiveness by clogging the soil or sealing the surface and reducing the volume available for stormwater storage.

19) Is the overflow or bypass structure clogged?

Bioretention practices typically have overflow structures instead of outlet structures. Outflow for a bioretention practice is intended to go into the soil such that deep percolation or evaporation occurs. The overflow structure should be free of any debris, sediment, vegetation, and other obstructions so that stormwater runoff can easily exit the bioretention practice in the event of a large storm event. If the overflow structure is partially or completely clogged, surrounding areas may be flooded by stored stormwater runoff. Any obstructions should be removed immediately to ensure proper operation of the bioretention practice.

20) Is the overflow structure askew or misaligned?

Misaligned inlet or overflow structures often allow stormwater runoff to enter or exit a bioretention practice by means other than those intended by design or prevent stormwater runoff from entering the practice at all. This condition can result in erosion, channelization, or flooding of surrounding areas, which can further exacerbate the misalignment or create other problems.

Inlet and overflow structures can become misaligned for several reasons, including frost heave of the soil, vehicular collision, and geotechnical failure. Misaligned inlet or overflow structures should be repaired or replaced as soon as possible to reduce detrimental impact. Any obstructions should be removed immediately to ensure proper operation of the infiltration practice.

E.4. References

Brown, E., D. Caraco, and R. Pitt. 2004. Illicit Discharge Detection and Elimination: A Guidance Manual for Program Development and Technical Assessment. Center for Watershed Protection, Ellicott City, MD.

Minnesota Stormwater Steering Committee. 2005. The Minnesota Stormwater Manual. Developed by Emmons and Olivier Resources for the Stormwater Steering Committee, Minnesota Pollution Control Agency, St. Paul, MN. http://www.pca.state.mn.us/water/stormwater/stormwater-manual.html

Munsell. 2007. Munsell Soil Color Chart. http://soils.usda.gov/education/resources/k_12/lessons/color/

Shaw, D. and R. Schmidt. 2003. Plants for Stormwater Design: Species Selection for the Upper Midwest. Minnesota Pollution Control Agency, St. Paul, MN.

Appendix F: Case Study - Assessment of infiltration at a rain garden

The University of Minnesota (U of M), St. Paul campus rain garden is located on Gortner Avenue and Commonwealth in the Mississippi River watershed. There are five rain gardens located along Gortner Avenue, and three of them are in series. Basins C and B are connected to basin D by two drop structures consisting of bricks and serve as overflow basins. The assessment was conducted on the basin D rain garden. The rain gardens were designed by Barr Engineering and installed in October of 2004. A thorough assessment was conducted on basin D in the summer of 2006.

Basin D rain garden is approximately 960 square feet in size with a ponding depth of 0.5 feet. The design plans indicate 960 square feet with a ponding depth of 2 feet. It is designed to provide storage for the maximum amount of water the space would allow. Storm water runoff is directed to the rain garden using two inlets, a curb cut off of Gortner Avenue located along the northwest corner of the rain garden, and an inlet pipe located at the center of the north border of the rain garden, which is connected to the stormwater sewer system. The storm sewer inlet pipe has a 5 inch by 12 inch sub-grade of Fond Du Lac wall stone to prevent erosion. The native soil was excavated and filled with a sand trench to a depth of 3-4 feet and a width of 3 feet in the center of the basin. Clean sand with only 5% passing through a 200 micron sieve was used for the sand trench. Basin D rain garden was designed to infiltrate the maximum storage volume within 24 hours. This results in an estimated infiltration rate of 0.5 inches/hour. The basin was then filled with planting topsoil to a depth of 8 inches and planted with selected vegetation. The plant design plan is shown in Figure F.1.

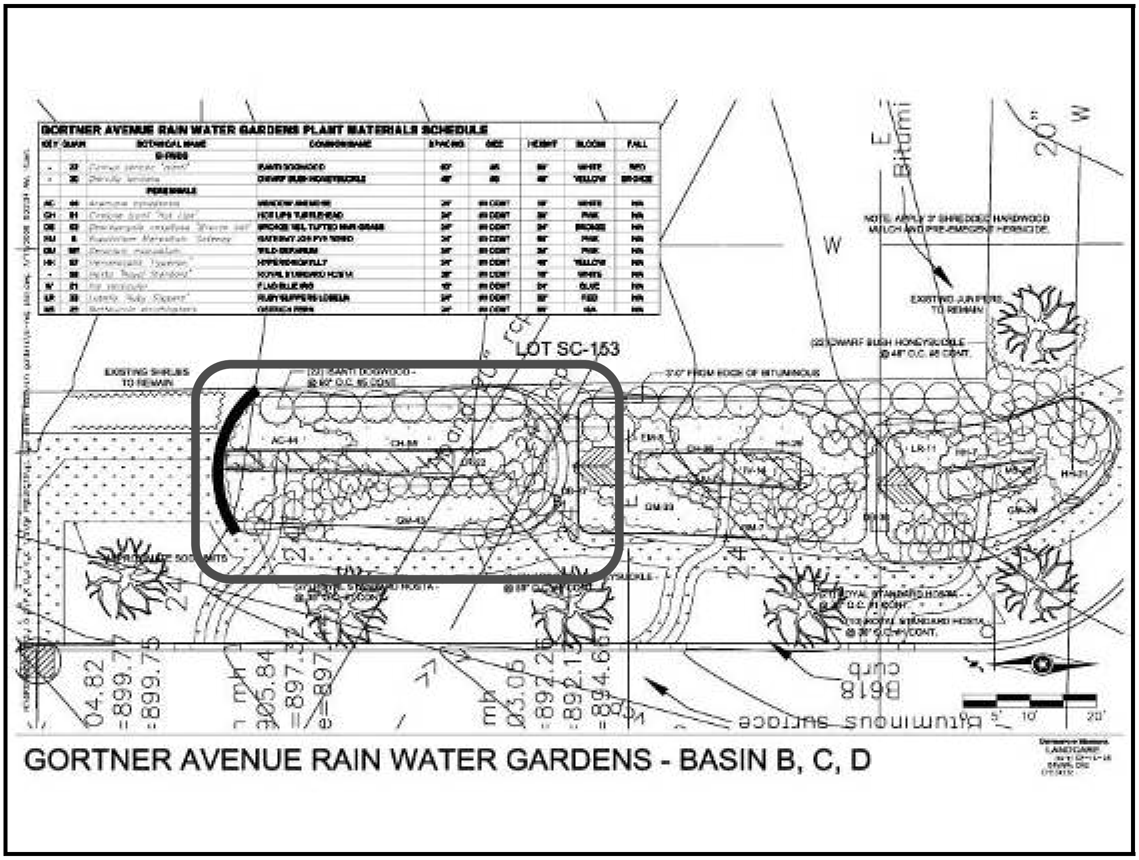

Figure F.1. U of M - St. Paul campus plant design plan.

F.1. Assessment Goals

The purpose of the assessment was to determine if the rain garden had the ability to infiltrate stormwater runoff at the appropriate rate. Rain gardens are typically designed to drain within 48 hours after a storm event. Three of the four levels of assessment as described in chapter 3 of the *Assessment of Stormwater Best Management Practices Manual* were conducted: visual inspection, capacity tests, and a synthetic runoff test.

F.2. Visual Inspection

F.2.1. Assessment Techniques

The visual inspection of rain gardens consists of two components, a vegetation analysis and an inspection of the soil. The vegetation analysis examines the species of vegetation present in comparison with the design plans, apparent health of the plants, percent cover of vegetation, and presence of invasive weeds and/or wetland plants. The original plant design was used along with a plant field guide to identify the species present. The leaf color, height and width of the plants were examined and described as poor, fair, or good. The site was examined for bare spots and a percent of the vegetation cover was determined. Several photographs of the plants were taken to serve as a record of the vegetation.

The inspection of the soil was conducted by evaluating several soil properties; soil texture and color, soil moisture, and bulk density. These procedures can be found in the Soil Science Society of America Book Series: 5, Methods of Soil Analysis, Part 1- Physical and Mineralogical Methods (Klute 1986). Soil texture can be determined from a sample using sedimentation procedures or in the field using a field guide. The textural flow chart, found in Chapter 11 of the *Assessment of Stormwater Best Management Practices Manual*, was used to determine the texture of the soil. Soil color was determined using a Munsell® soil color chart (Munsell 2007) and was done for each new layer (signified by a change in texture or color). Figure F.2 is a photograph of the texture and color of the soil being determined in the field using the USDA textural triangle, textural flow chart, and the Munsell® soil color chart. There are several methods available for measuring soil moisture or a general wetness can be described. When making general wetness statements the terms dry, moist, saturated and inundated are typical descriptions. The soil moisture was measured at this site using two methods; the gravimetric method and with the use of a capacitance probe. The final soil property measured was the bulk density. Bulk density can be used to convert gravimetric water content to volumetric water content, calculate porosity and void ratio when particle density is known and is a useful index of the degree of compaction. The core method was used to measure bulk density. Additional observations were made regarding channelization, sediment accumulation, erosion and condition of inlet structures.

F.2.3. Assessment Results

The plants in the rain garden matched up fairly well to the design plans, although there appeared to have been some modifications made to the original design plan. Most of the plants appeared to be healthy with the exception of geraniums along the west edge. They were not filling in the area as they should and their growth was not as full as expected. There was a fairly large bare spot northeast of the center of the basin where the anemones and chelone come together.

Figure F.2. Texturing and coloring the soil.

The overall percent plant cover of the basin was roughly 70%. There were a large bare spot near the inlet and up the side slope next to the curb inlet. The vegetation was sparse in the center of the basin with several large bare spots between plants. There did not appear to be a large number of weeds present, and there was no sign of wetland vegetation. Based on the visual inspection of the vegetation there appears to be some limitation of plant growth.

The inspection of the soil included soil texture and color, soil moisture and bulk density. The soil texture and color is as follows:

- 0 – 8 inches: Sandy Loam, 10YR 2/2
- 8 – 19 inches: Silt Loam, 10YR 2/1
- 19 – 47 inches: Sand (non-native), 10YR 6/4
- 47 - ? inches: Silt Loam with coarse Sand, 2.5YR 3/3

The sandy loam topsoil is typical for rain gardens in Minnesota; however the silt loam layer below is of concern. When comparing the two soils on the USDA Soil Textural Triangle, it shows that there is a much higher percentage of silt which is finer than sand and has a lower K_{sat} than the sandier layer above and below it. In this situation the silt loam layer controls the water from flow through the entire soil profile. The original design plans indicate 3 to 4 feet of the non-native sand directly below the 8 inch layer of topsoil. The soil moisture of the basin was near saturation most of the time. This indicates that there is sufficient water for plant growth with adequate drainage. The mulch layer and canopy cover over the soil surface are likely contributing to the retained moisture during the dry season. The bulk density of the site varied spatially, with an average of 1.182± 0.127grams per cubic centimeter. This is lower than the typical 1.3 grams per cubic centimeter for most mineral soils, however with the high amount of organic matter due to the mulch and plant roots this appears to be normal for rain gardens. There were no signs of hydric conditions such as gleying or the presence of mottles. Based on inspection of the soil properties the infiltration appears to be adequate, however the restrictive layer of silt loam may pose problems for long term operation by retaining too much water during large storm events. No signs of erosion or channelization were present near the inlet structure. Both inlet structures were in good condition.

F.3. Capacity Testing

F.3.1. Assessment Techniques

The permeability of the soil was measured to determine the rain garden's capacity for infiltrating water. At this site several devices were used to measure the saturated hydraulic conductivity (K_{sat}) of the soil in order to establish the technique. The three devices used to measure K_{sat} were the double-ring infiltrometer, Minidisk infiltrometer, and the Modified Philip-Dunne infiltrometer. Locations where point measurements of K_{sat} were to be made were distributed evenly throughout the entire rain garden and marked using orange utility flags. These locations varied in their proximity to the vegetation but were never placed directly over the base of the plant. Additional locations were marked at the low point of the site to better represent the frequently occurring small runoff events. Figure F.3 is a photograph of the rain garden with utility flags marking test locations.

Figure F.3. Photograph of flags marking locations of permeability tests.

A total of 40 locations were marked in this site to evaluate the spatial variability of K_{sat} within the basin. The data was compiled and used to create a graph to estimate the appropriate number of measurements necessary to obtain an accurate average value of K_{sat} for the entire basin. This graph can be found in Appendix D and should be used as a suggestion for conducting capacity tests at other sites. The coordinates of each location as well as the perimeter of the rain garden was determined using a GPS device. At 40 of the test locations a measurement was made using the Modified Philip-Dunne infiltrometer and another measurement was made using the minidisk infiltrometer. At the two locations two measurements (duplicates) were made using the Modified Philip-Dunne infiltrometer and two measurements were made using the minidisk infiltrometer. The double-ring infiltrometer was only used to make measurements at two of the locations due to its large size, and large time and water requirements. Each location was allowed to dry out between measurements.

The double-ring infiltrometer is a constant head infiltrometer and requires two sources of water, one for the inner ring and one for the outer ring. The inner ring had a diameter of 8 inches and the outer ring diameter was 16 inches. Constant head was maintained in the inner ring of the double-ring using a Mariotte system. The system used in the field is shown in Figure F.4. Water level s inside the plastic container shown and time measurements were recorded once steady state was achieved. For detailed instructions on double-ring infiltrometer procedures see Soil Science Society of America Book Series: 5, Methods of Soil Analysis, Part 1-Physical and Mineralogical Methods (Klute 1986).

Figure F.4. Photograph of double ring infiltrometer with Mariotte system.

The Minidisk infiltrometer was purchased through Decagon Devices and is a compact disc infiltrometer. This is a transient flow device in which water is delivered to the soil surface through a porous disc at a negative pressure. This technique is used to prevent water from flowing through large macropores and results in a K_{sat} value representative of the soil matrix itself. This particular device required change in water volume with time measurements to be recorded. These data were then input into a Microsoft Excel ® spreadsheet provided by the manufacturer.

The Modified Philip-Dunne infiltrometer is a falling head infiltrometer constructed specifically for this project; see Appendix D for detailed instructions on the construction. The device was uniformly pounded into the soil to a depth of 5 cm. The initial soil moisture was measured at five locations around the base of the Modified Philip-Dunne infiltrometer using two methods; the gravimetric method and with a capacitance probe. Mulch from the rain garden was placed inside the device to prevent erosion; water was then poured into the device to the desired height, which was 43 cm for this site. Two sets of change in water level with time measurements were made for additional data. The first set was the visual method which requires an initial height of water at time zero, a time at the half way point (21.5 cm), and a time at empty. The second method made continuous measurements using an ultrasonic sensor. The soil moisture was then measured from directly inside the device, again at five locations. For more detailed instructions on the use of the Modified Philip-Dunne infiltrometer see Appendix D. The original Philip-Dunne equations (Philip 1993), Equation F.1 below, were modified and the data collected was then used to calculate K_{sat}. A Microsoft Excel ® spreadsheet was developed to input the measured parameters and calculate K_{sat}. An example of the spreadsheet can be seen in Table F.1; the highlighted cells indicate the necessary input parameters. In depth procedures for calculating K_{sat} using the Modified Philip-Dunne infiltrometer data can be found in Appendix D. Figure F.5 is a photograph of the Modified Philip-Dunne infiltrometer being used in the field with an ultra sonic sensor for continuous measurements.

Equation F.1. Equation to calculate K_{sat} (Munoz-Carpena et al., 2002).

$$K_s = \frac{\pi^2 r_o \tau_{max}(a)}{8 t_{max}}; \psi_f = \frac{(a^3 - 1) r_o \Delta\theta}{3} - h_o - \frac{\pi^2 r_o}{8}$$

Table F.1. Microsoft Excel ® spreadsheet used to calculate K_{sat} using the data collected from the Modified Philip-Dunne infiltrometer test.

Measured Variables	**Notation**	**Value**	**Units**
initial volumetric moisture	θ_i	14.4%	
final volumetric moisture	θ_f	47.8%	
length of device below surface	L_{max}	5.0	cm
radius of device	r_1	5.0	cm
phase one initial height	H_0	43.4	cm
Computed Variables	**Notation**	**Value**	**Units**
change in volumetric moisture	$\Delta\theta$	0.3341	
hemispherical source radius	r_0	2.50	cm
capillary pressure	C	-4.92	cm
mean hydraulic conductivity	K	4.38E-03	cm/s
Sum of Error Squared		1587.2927	
Check Solver Installation			
Autofill Columns			
Solve for R(t)			
Solve for K and C			
Clear Template			

Figure F.5. Modified Philip-Dunne infiltrometer with ultrasonic sensor.

F.3.2. Assessment Results

After the 40 locations where point measurements were made were positioned using GPS they were input into ArcView. Figure F.6 is an ArcMap of the measurements made using the Modified Philip-Dunne infiltrometer. The results of the measurements made with the other devices as well as the Modified Philip-Dunne infiltrometer are shown in Figure F.7. Both figures illustrate how K_{sat} varies both spatially and among the devices. The average K_{sat} for the double ring infiltrometer, Minidisk infiltrometer and the Modified Philip-Dunne infiltrometer were: 0.999 in/hr, 0.519 in/hr, and 4.157 in/hr, respectively. All of the devices used to measure K_{sat} are based on different theories of flow through the soil and different assumptions regarding the system. Currently none of the devices mentioned have the ability to account for the presence of macropores or other preferential flow paths found in the soil. Chapter 4 of the *Assessment of Stormwater Best Management Practices Manual* presents a detailed discussion of the theories of infiltration as well as the devices used to measure infiltration.

As a result of an evaluation of the devices based on this field work as well as previous work (see Table D.1 in Appendix D), the Modified Philip-Dunne infiltrometer was found to be most desirable, and is recommended for future assessment of infiltration/filtration practices. For more time-efficient assessment it is recommended to use multiple Modified Philip-Dunne devices. This level of assessment (i.e. Level 2) was determined to be the most beneficial technique for understanding the spatial variability of the site and developing a maintenance schedule for the practice.

The time required to drain the design storage volume can be estimated using the measured saturated hydraulic conductivity value of 0.519 in/hr as a conservative estimate of infiltration rate. With this infiltration rate and the known design depth of 6.125 in., the drain time can be estimated by dividing 0.519 in/hr into 6.125 in. to get 12 hours.

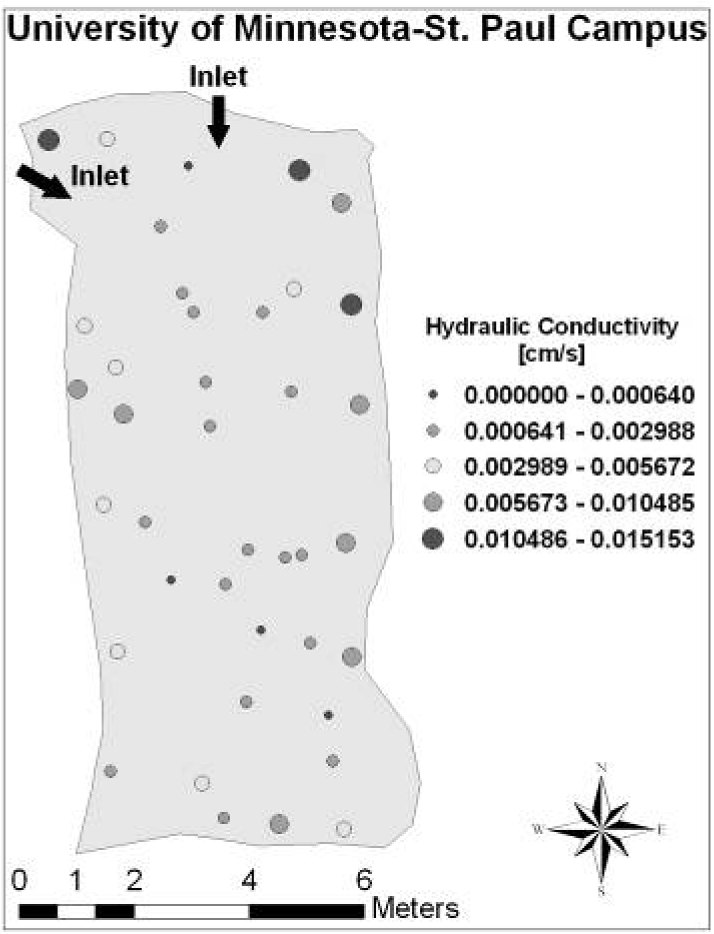

Figure F.6. ArcMap of K_{sat} using the Modified Philip-Dunne (MPD) infiltrometer measurements.

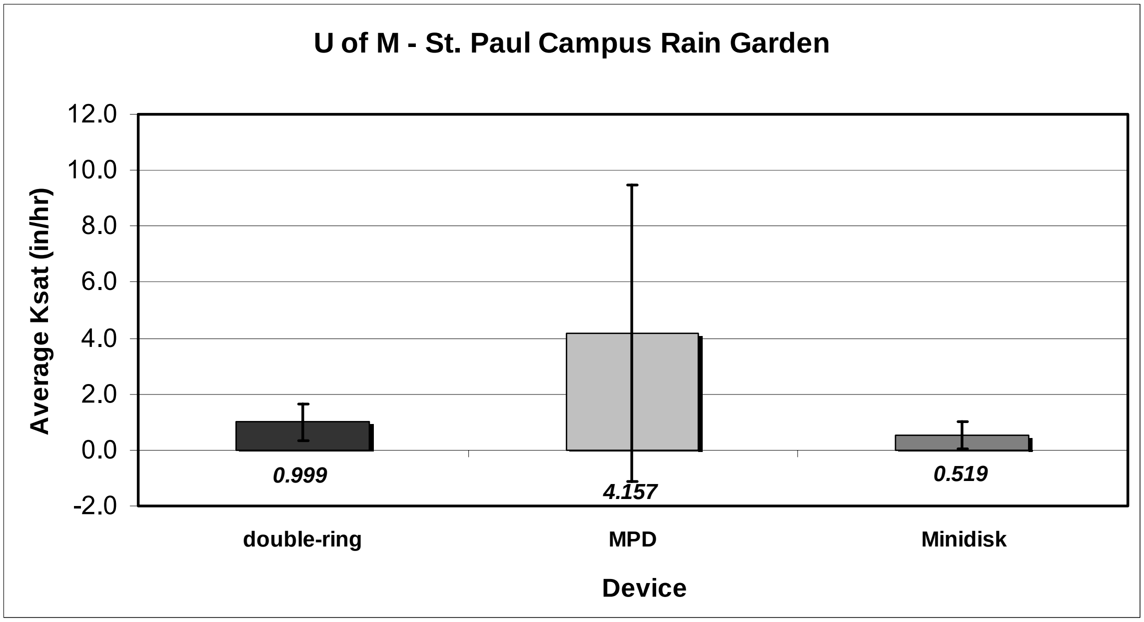

Figure F.7. Comparison of measured median K_{sat} using three infiltration devices.

F.4. Synthetic Runoff Test

F.4.1. Assessment Techniques

It was desired to conduct a synthetic runoff test at the site to measure the time required to drain the maximum storage volume. To determine if the nearby fire hydrant could provide the necessary flow, the analysis procedure detailed in example 10.1 was performed. In summary, the water quality volume (WQV) of the rain garden was estimated by multiplying the surface area of 960 ft^2 by the design depth of 0.5 ft and then multiplying it by 1/3 (volume of a pyramid) to get the WQV of 163.3 ft^3. Assuming the infiltration rate measured with the Modified Philip-Dunne method of 4.157 in/hr exists when filling the rain garden and that it is desired to fill the rain garden in 30 minutes (i.e. 1800 sec), the required flow from the hydrant was calculated to be 0.18 ft^3/s by solving the following equation:

$$163.3\,ft^3 = (Q_{req})(1800\sec) - (4.157 in/hr)(1in/12ft)(960ft^2)(1hr/3600s)(1800\sec)$$

Where Q_{req} is the discharge the hydrant must supply if the rain garden is to be filled in 30 minutes. Since fire hydrants can typically provide flow up to 3 cubic feet per second (1,500 gal/min), it was determine that the required flow could be obtained from the nearby fire hydrant.

Prior to flooding the site an ultrasonic sensor was positioned directly above the low point of the basin to make continuous water level measurements over time. A bare spot within the basin was chosen to provide a good reflective surface for the sound waves. The hydrant was then prepared by connecting a 2.5 inch fire hose to the hydrant using a safety valve to ensure no back flow would occur. The fire hose discharged water into the storm sewer manhole closest to the basin until the rain garden was filled to capacity. Permission and assistance was provided by the University of Minnesota facilities management who provided all of the proper connectors, valves and hoses for the fire hydrant. After the water stopped flowing into the basin the water level was measured and the timer started. Continuous measurements using the ultrasonic sensor as well as visual measurements with a yard stick were made until the basin was completely drained.

F.4.2. Assessment Results

Figure F.8 is a graph displaying the change in water level with time using the data collected from the ultrasonic sensor. The synthetic runoff test represents the drain time of two hours when the rain garden is filled to capacity. This is about six times shorter than the conservative estimate of 12 hours using the Minidisk infiltrometer results which was obtained by assuming the saturated hydraulic conductivity value was equal to the infiltration rate.

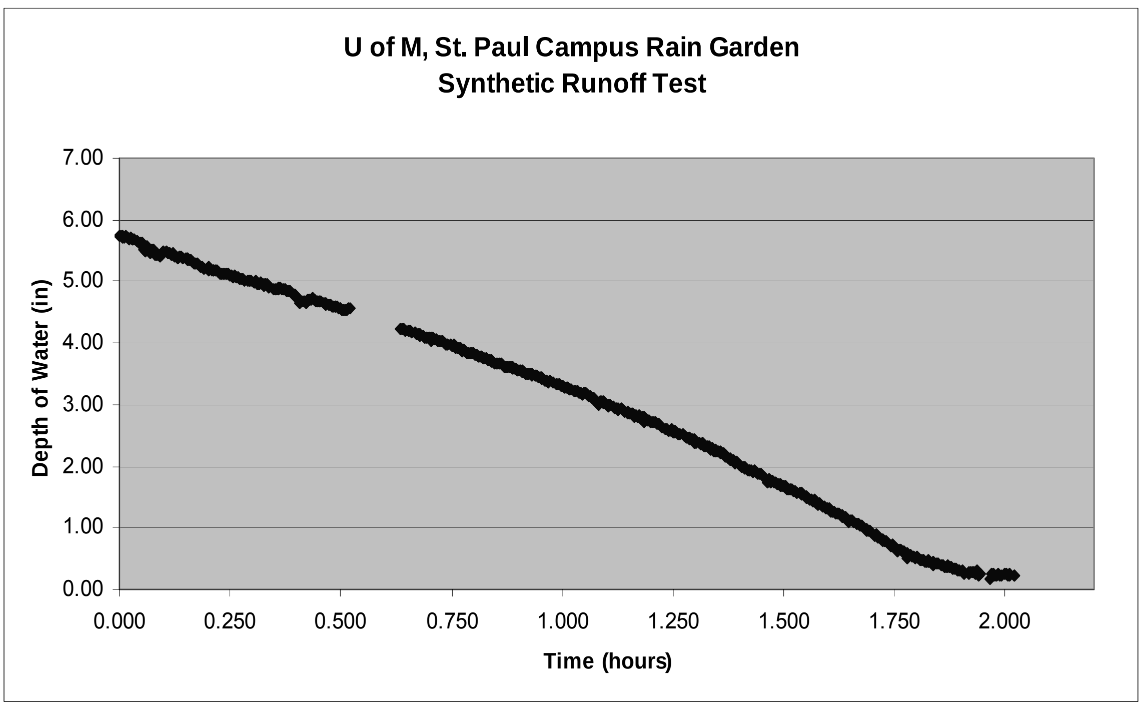

Figure F.8. U of M, St. Paul synthetic runoff rest results from the ultrasonic sensor readings.

F.5. Conclusions and Recommendations

The overall performance of the basin D rain garden is satisfactory. The results of the visual inspection indicate that there are some concerns for a few of the plant species. These particular species should be further evaluated to eliminate possible causes of growth limitation. Some examples of possible growth limiters include: improper soil moisture regime, improper sun/shade location, limited oxygen in the soil, high levels of salt in the soil, the presence of invasive species and several other plant specific requirements not being met. The center of the basin had near saturated soil conditions during the dry season and therefore the plants located in this region should represent a wet meadow plant community. Despite the issues near the inlet and in the center of the basin the majority of the vegetation was in good health and provided sufficient cover. The soil inspection indicates the potential for problems for large runoff events. The silt loam soil layer just below the topsoil and above the sand trench will result in restricted infiltration to the sand trench due to the smaller pore sizes and increased holding capacity of that particular layer. A more thorough inspection of the soil layers throughout the basin should be conducted to determine the extent of the restrictive layer. The distribution of infiltration rates also indicates that there is a problem with the soil in the center of the basin. All of the very low infiltration rates were located in the center of the basin, which is also where the soil core was taken to characterize the soil layers of the basin. This indicates that the restrictive soil layer could be causing these lower infiltration rates in the center of the basin. The side slopes of the basin had high infiltration rates. Table F.2 summarizes the results from the capacity testing and synthetic runoff testing to determine whether stormwater will drain within the specified 48 hours.

To determine the time it will take for the basin to drain using the capacity testing results first use the dimensions of the basin to calculate the surface area and the storage volume. The infiltration discharge can then calculated by multiplying the surface area by the measured K_{sat}. The time to drain the storage volume can be estimated by dividing the storage volume by the infiltration discharge. Or, as an alternative approach that was previously used in section 3, divide the design depth by the infiltration rate. Each method for measuring K_{sat} of the soil can result in different values due to the theory of flow they are designed for and the scale of the measurements. The results from the measurements made with the minidisk infiltrometer would represent the minimum value for the soil, and the synthetic runoff test represents the drain time when the basin if filled to its holding capacity. The double ring infiltrometer and the Modified Philip-Dunne infiltrometer capture a percentage of the macropores present in the soil, but cannot account for the total spatial variability of the rain garden. To estimate a conservative drain time the results from the Minidisk infiltrometer may be used as it represents the permeability of the soil matrix itself excluded preferential flow occurring through root channels or other macropores. However the parameters which are used to calculate K_{sat} using the minidisk infiltrometer are estimates and may provide inaccurate results if the correct parameters are not chosen. The Modified Philip-Dunne infiltrometer has been determined to provide the most accurate existing K_{sat} values (see Table D.1 in Appendix D), however the measured K_{sat} values will likely change over time as the macroporosity of the soil changes. Time, environmental conditions, vegetation, and soil properties all influence the infiltration rate of rain gardens and should be monitored periodically.

Table F.2. Comparison of device and synthetic runoff test measurements according to drainage time.

Dimensions		**Storage Volume**					
L (ft) =	48	WQV (ft^3) =	163.3				
W (ft) =	20						
h (ft) =	0.51						
S.A. (ft^2) =	960						
Infiltration Rates							
Double-Ring		Minidisk		MPD			
K_{sat} (ft/day) =	1.997	K_{sat} (ft/day) =	1.337	K_{sat} (ft/day) =	12.131		
Infiltration Discharge							
Double-Ring		Minidisk		MPD			
I.D. (ft^3/day) =	1917	I.D. (ft^3/day) =	1283	I.D. (ft^3/day) =	11646		
Drain Time							
Double-Ring		Minidisk		MPD		Flood Test	
Time (hrs) =	2.045	Time (hrs) =	3.054	Time (hrs) =	0.337	Time (hrs) =	2.117

The synthetic runoff test indicated very good infiltration when the basin is filled to the maximum storage volume and the median results of the capacity tests are better estimates for typical rainfall events. Additional synthetic runoff test at varying depths should be conducted to understand how the basin drains for smaller rain events. Although there appears to be some concerns regarding the basin, drainage time is well below the designed 48 hours. The low infiltration and sparse cover of vegetation occurring in the center of the basin should be further evaluated and amended to prevent failure of the basin in the future. A maintenance schedule should be developed based on this evaluation to ensure adequate stormwater treatment efficiency.

F.6. References

Klute, A. 1986. Methods of Soil Ananlysis, Part I. Physical and Mineralogical Methods, 2nd edition. Soil Science Society of America, Inc. Publisher, Madison.

Munoz-Carpena, R., C. M. Regalado, J. Alvarez-Benedi, and F. Bartoli. 2002. Field evaluation of the new Philip-Dunne permeameter for measuring saturated hydraulic conductivity. Soil Science 167:9-24.

Munsell. 2007. Munsell Soil Color Chart. http://soils.usda.gov/education/resources/k_12/lessons/color/

Philip, J. R. 1993. Approximate Analysis of Falling-Head Lined Borehole Permeameter. Water Resources Research 29:3763-3768.