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PERFORMANCE ASSESSMENT OF RAIN GARDENS[1]

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ABSTRACT: The most widely used approach for evaluating the performance of stormwater best management practices (BMPs) such as rain gardens is monitoring, but this approach can involve a long time period to observe a sufficient number and variety of storm events, a high level of effort, and unavoidable uncertainty. In this paper, we describe the development and evaluation of three approaches for performance assessment of rain gardens: visual inspection, infiltration rate testing, and synthetic drawdown testing. Twelve rain gardens in Minnesota underwent visual inspection, with four determined to be nonfunctional based on one or more of the following criteria: (1) presence of ponded water, (2) presence of hydric soils, (3) presence of emergent (wetland) vegetation, and (4) failing vegetation. It is believed that these rain gardens failed due to a lack of maintenance. For the remaining eight rain gardens, an infiltrometer was used to determine the saturated hydraulic conductivity (K_{sat}) of the soil surface at several locations throughout each basin in what is termed infiltration rate testing. The median K_{sat} values for the rain gardens ranged from 3 to 72 cm/h. Synthetic drawdown testing was performed on three rain gardens by filling the basins with water to capacity where possible and recording water level over time. The observed drain times for two of those rain gardens were in good agreement with predictions based on the median of the infiltrometer measurements. The observed drain time for the third rain garden was much greater than predicted due to the presence of a restrictive soil layer beneath the topsoil. The assessment approaches developed in this research should prove useful for determining whether the construction of the rain garden was performed properly, a rain garden is functioning properly, and for developing maintenance tasks and schedules.

(KEY TERMS: rain garden; bioretention practice; infiltration; best management practices; runoff; stormwater management.)

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INTRODUCTION

Urbanization of a watershed has significant negative effects on downstream aquatic systems including degradation of both form and function (Booth and Jackson, 1997). The increase in runoff caused by increases in impervious land area during urbanization results in an increase in flood frequency and can decrease base flows (Wang *et al.*, 2001). These

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hydrologic changes result in widening and increased instability of stream channels, increase sediment loads, and degradation of fish habitat (Booth and Jackson, 1997). In addition to sediments, urban runoff often contains a wide variety of other pollutants including: nutrients, oxygen-demanding substances, pathogens, road salts, petroleum hydrocarbons, heavy metals, and excess thermal energy (USEPA, 2005). Such pollutants could cause further degradation of aquatic habitat as well as limit or eliminate recreational uses.

In response to the degraded water quality found in our waterways due to urban stormwater runoff, the Clean Water Act requires the regulation of municipal separate storm sewer systems (MS4s) and the implementation of a two-phase Storm Water Pollution Prevention Program (SWPPP) (USEPA, 2007). The SWPPP requires discharge detection and elimination, construction and postconstruction runoff control, and pollution prevention measures. Key to pollution prevention efforts in urban areas are the installation and maintenance of stormwater best management practices (BMPs). For example, low impact development (LID) stormwater BMPs, such as rain gardens and bioretention facilities, are commonly used to infiltrate stormwater to reduce outfall stormwater runoff volume and improve water quality via filtration and other processes. These systems are gaining interest among MS4s due to their low impact, potential effectiveness, and high esthetic value. Currently, there is little guidance on how to properly assess the effectiveness of LID stormwater BMPs after installation. Consequently, information is lacking concerning how well these stormwater BMPs perform immediately after installation, how they perform over time, and when maintenance may be required. Guidance is needed regarding assessment of the effectiveness of LID stormwater BMPs such as rain gardens.

Currently, comprehensive water quantity and quality monitoring is the most widely used approach for evaluating the performance of stormwater BMPs (USEPA, 2002). Monitoring typically involves the collection of stormwater grab samples for analysis of pollutant concentration and determination of the water budget of the BMP using flow measurement devices at all inflow and outflow locations, data loggers, and related equipment. Monitoring is especially useful for watershed-scale studies to assess overall pollutant loads to receiving waters and the impact of a group of stormwater BMPs on these loads. Monitoring of individual stormwater BMPs, however, is often impractical due to the long time period (one or more rainy seasons) required to observe a sufficient number and variety of storm events, the effort to setup and maintain such a system, and uncertainty in the results (Weiss *et al.*, 2007) as a natural storm event can neither be controlled nor repeated. This is especially true for rain gardens, which are often small (<150 m^2), simple, stormwater BMPs that are widely distributed throughout urban and suburban neighborhoods. Therefore, alternatives to typical monitoring protocols are needed for assessing the performance of rain gardens.

In this paper, we discuss the development and evaluation of three alternative suggested approaches for rain garden evaluation: (1) visual inspection, (2) infiltration rate testing, and (3) synthetic drawdown testing. These assessment approaches differ in terms of the effort required and the information obtained. *Visual inspection* involves examination of the inlet and outlet structures, vegetation, and soil and is used to quickly determine if a rain garden is malfunctioning and in need of maintenance or replacement. *Infiltration rate testing* involves the use of infiltrometers to determine near-surface saturated hydraulic conductivity (K_{sat}) throughout a rain garden. In *synthetic drawdown testing,* a fire hydrant or water truck is used to fill the basin with water and the overall drain time of the rain garden is determined. They are described more fully in the next section.

LEVELS OF ASSESSMENT OVERVIEW

Visual Inspection (Level 1)

The visual inspection may be simple or comprehensive depending on the site conditions and the purpose of assessment. Simple observations, such as visiting a site after a storm event to check for standing water, are valuable and require less effort (1 h), although limited information is obtained. A comprehensive visual inspection requires some knowledge of both vegetation and soils and requires roughly 4 h to complete. For verification of proper construction and determination of long-term functionality, it is recommended that additional assessment be performed even if no problems are found during the visual inspection. This more detailed assessment will be of interest to officials that certify rain gardens.

Infiltration Rate Testing (Level 2)

The ability of a rain garden to infiltrate water under saturated (flooded) conditions can be estimated by determining K_{sat} at a number of locations throughout the stormwater BMP using permeameters or infiltrometers. Five field devices [Double-Ring Infiltrometer, Guelph Permeameter (Rickly Hydrological Company, Columbus, Ohio), Modified Philip-Dunne (MPD) Infiltrometer (Nestingen, 2007), Minidisk Infiltrometer (Decagon Devices, Inc., Pullman, Washington), and Tension Infiltrometer] for determining the K_{sat} of surface soils were evaluated by Nestingen (2007). The MPD Infiltrometer developed in our laboratory was selected due to the minimal volume of water necessary (to run the test), ease of use in the field, low cost of the device, and transportability of the equipment. With the MPD Infiltrometer (Figure 1), 30-40 individual measurements in one rain garden can be completed in one day, with additional time required to perform the data analyses. The K_{sat} results from such an investigation can be used to predict the drain time of the basin, which is useful for routine evaluation and determining whether a rain garden was properly installed. Also, tracking infiltration performance over time via infiltration rate testing at the same locations throughout the rain garden provides long-term data that can be used to develop a maintenance schedule when changes in infiltration rates are seen. Furthermore, the spatial distribution of the measured K_{sat} values can be used to identify low permeability areas within a rain garden that require rehabilitation.

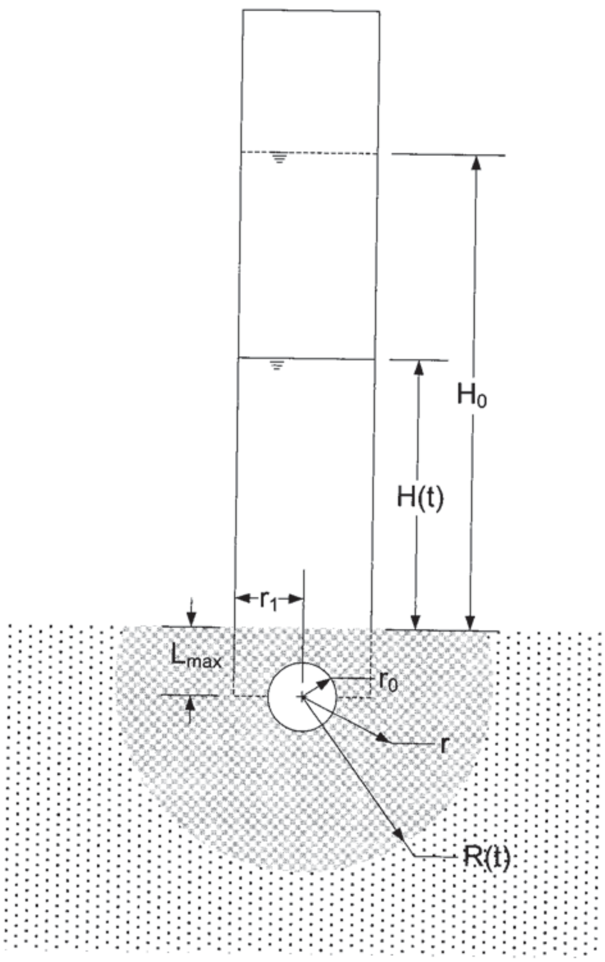

FIGURE 1. Important Parameters of the Modified Philip-Dunne Infiltrometer (Nestingen, 2007). H_0 is the initial height of water, $H(t)$ is the height of water at time t, L_{max} is the depth of insertion into the soil, r_0 is the equivalent source radius, r_1 is the radius of the cylinder, r is any radius within the wetted front, and $R(t)$ is the radius to the sharp wetted front at time t.

Synthetic Drawdown Testing (Level 3)

As with any soil system, infiltration rates can vary substantially at small distances. This test is an averaging approach for events sufficient to fill the entire surface volume of the rain garden. Synthetic drawdown tests, like the infiltration rate testing, provide the time required for the stormwater BMP to drain when the rain garden encounters a storm. Once permission to use a fire hydrant has been obtained or arrangements to use a tanker truck have been made, a single test will require less than one day to complete. A large tanker truck contains ~27 m^3 and most fire hydrants may be used with permission to supply between 0.07 and 0.15 l/min for 20 min, to give 80-160 m^3. After filling the basin to the desired level, the water level is measured over time and the time required to completely empty the basin (i.e., the drain time) is recorded. The main advantages of a synthetic drawdown test (in comparison to infiltration rate testing) are that it provides a direct measure of the rain garden drain time and it potentially can be used to assess pollutant removal efficiency. The main disadvantages are that the size of a rain garden that can be tested is limited because of typical water supply constraints and no information on spatial variability in infiltration performance within a rain garden is obtained.

The above-mentioned assessment techniques, along with continuous monitoring by placing automatic monitors upstream and downstream of the device (Level 4), can be used individually or in combination, depending on the goals of the specific assessment program. This has been termed a four-level BMP assessment approach (Gulliver and Anderson, 2007). For example, if the goal is to calculate the runoff volume reductions provided by the rain gardens in a watershed, the Levels 2 and/or 3 (infiltration rate testing and synthetic drawdown testing), should provide adequate information. If the goal is to calculate pollutant load reductions for a Total Maximum Daily Load study, then synthetic drawdown testing and water quality monitoring may be required. If the goal of the assessment is to simply satisfy state permit requirements then a routine visual inspection may be all that is required. For developing maintenance schedules, and checking functionality over the longer period, a combination of visual inspection and infiltration rate testing is recommended.

SITE SELECTION AND DESCRIPTIONS

Twelve sites in Minnesota were selected for the development and evaluation of the rain garden assessment during the 2006 field season (spring through fall). These sites were selected based on the following criteria: (1) permission and participation from the owner/operator of the site, (2) availability of site information (e.g., site plans, planting diagrams, etc.), and (3) proximity to the University of Minnesota (UM). A summary of the rain garden characteristics and the levels of assessment used at each site are provided in Table 1.

The areas of the rain gardens ranged from 28 to 1,350 m^2. The smallest rain garden was located in a residential area and received 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. Three rain gardens were installed in the fall of 2003 and were online (i.e., receiving runoff) in the spring of 2004. Only the UM – Duluth (12) site had a pretreatment practice installed, a sediment forebay located at the inlet. Four of the rain gardens contained underdrains to compensate for the restrictive soils in the area.

METHODS AND ANALYSIS

Visual Inspection

The rain gardens were examined for obvious drainage problems or impediments to infiltration, such as ponded water present for more than 48 h after a rainfall event, sediment accumulation in the basin from the drainage area, clogged inlet or outlet structures, and excessive erosion within the rain garden. The vegetation was then assessed with consideration of the age of the rain garden, time of the growing season, species present and their growth requirements, and condition of the site. A visual assessment of the health of the plants was made by examining and recording the color, size, and quality of the leaves, stem, and flowers. The available design plans along with a plant field guide (Shaw and Schmidt, 2003) were used to determine whether the correct species were present. The percent vegetative cover was estimated to determine if plants were established. The sites were also inspected for the presence of wetland plant species (e.g., cattail, arrowheads, and marsh smartweed) to determine if hydric soils may be present, indicating prolonged periods of saturation. Photographs of each site were taken and observations made were recorded to develop a complete record of conditions at the time of assessment.

The depth at which rain gardens are installed varies greatly and is dependant on local factors such as drainage area, surface area available for the rain garden, and underlying native soil type. To determine the existing soil profile a single soil core was taken at each rain garden near the center of the basin (as a representative sample) to a depth of ~1.2 m. This was the maximum depth a standard auger could penetrate using a soil corer and was believed to be sufficient to profile the near-surface soils that are important to infiltration. The textures of the different soil layers in the core were determined in the field using the feel method (Thien, 1979) and the USDA Textural Triangle. The color of the soil from each distinct layer in the core was determined by matching with a color chip in a Munsell® soil-color charts (X-Rite, Grand Rapids, Michigan). Special attention was paid to soils that were gray in color or contain

TABLE 1. General Description of the Assessed Rain Gardens.

ID	Rain Garden Name	Size (m^2)	Level of Assessment	Year Built	Source of Urban Runoff
1	Burnsville	28	1 and 2	2003	Residential street
2	RWMWD #4	29	1 and 2	2006	City street and office building roof
3	A[1]	46	1	1999	Parking lot and turf
4	B[1]	50	1	2001	Residential street
5	RWMWD #5	59	1, 2, and 3	2006	City street and office building roof
6	UM – St. Paul	67	1, 2, and 3	2004	Turf and street
7	Cottage Grove	70	1, 2, and 3	2002	Parking lot
8	C[1]	140	1	2001	Residential street
9	RWMWD #1	147	1 and 2	2006	City street and office building roof
10	D[1]	180	1	2001	Residential street
11	Thompson Lake	278	1 and 2	2003	Parking lot
12	UM – Duluth	1,350	1 and 2	2005	Parking lot

Notes: RWMWD, Ramsey-Washington Metro Watershed District; UM, University of Minnesota.
[1]Permission to publish the locale of these sites was not obtained.

mottles (i.e., small areas of gray, red, yellow, brown, or black that differ in color from the bulk soil), which may indicate hydric soils (Richardson and Vepraskas, 2001) that would be associated with prolonged water saturation. The soil was crumbled and repacked into the core hole after soil inspection was complete.

Infiltration Rate Tests

The MPD Infiltrometer (Figure 1) consists of a thin-walled (2 mm thick) aluminum cylinder with a height of 45 cm and an inner diameter of 10 cm. A transparent piezometer tube was attached to the outside of the device beside a measurement tape for making water level readings. After any mulch or detached/decaying plant material was brushed aside the device was pounded into the soil to a depth of 5 cm and then filled with water to a height of 43 cm as to not overflow the device. The water level over time was then recorded either manually or automatically using an ultrasonic sensor (1 reading/s averaged over 10 s) (MassaSonic, M-5000; MASSA PRODUCTS CORPORATION, Hingham, Massachusetts). MPD Infiltrometer measurements were made at a number of locations throughout each basin, based upon a restricted sampling grid that avoided bushes, trees, and energy dissipation structures such as riprap or concrete, and did not otherwise destroy plantings. The coordinates of each location were determined using a Trimble ProXR GPS unit (Trimble Navigation Limited, Sunnyvale, California), which delivers submeter accuracy (accuracy varies with proximity to base station) in the correct conditions. Six MPD Infiltrometers were used at a time to increase the rate of data collection.

The MPD Infiltrometer and the notations used in the equations are illustrated in Figure 1. The original Philip-Dunne permeameter technique involved placing the device in a borehole. The device was therefore modified to incorporate surface infiltration and capture any effects of sediment accumulation in the stormwater BMP. Due to these modifications in the technique, the methodology described by Philip (1993) for determining saturated hydraulic conductivity needed to be altered accordingly. This alteration included changing the geometry of the source from a sphere to a hemisphere and accounting for one-dimensional flow through the soil contained within the bottom of the device.

The equations used in calculating the saturated conductivity are only applied after $R(t)$ (radius to the sharp wetted front at time t) is greater than the distance $\sqrt{r_1^2 + L_{\max}^2}$, where r_1 is the radius of the cylinder and $L_{\max}$ is the depth of insertion into the soil, which can be determined from the volume of water infiltrated and soil porosity. The mass conservation equation for cumulative infiltration, $i(t)$, using the geometry of a spherical cap with a height of $R(t) + L_{\max}$ and soil with an initial and final moisture content of θ_0 and θ_1, respectively, is:

$$i(t) = \frac{\pi}{3}(\theta_1 - \theta_0)\left(2[R(t)]^3 + 3[R(t)]^2 L_{\max} - L_{\max}{}^3 - 4r_0^3\right) \tag{1}$$

The same analysis procedure described by Philip (1993) was followed, which involves working through a series of equations to solve for the two unknowns, K_{sat}, the saturated hydraulic conductivity and ψ which is the wetting front suction head for the unsaturated soil. A computational spreadsheet procedure with the solver add-in and visual basic application was developed to find solutions to the equations and automate the computational process and obtain values of K_{sat} and ψ.

For 57% of the tests, only three data points were obtained manually with the times corresponding to full, half-empty, and empty, as recommended by Munoz-Carpena *et al.* (2002) for the Philip-Dunne permeameter. The three-point method, however, required additional data processing to meet the requirements of the data fitting procedure used to determine K_{sat}. An exponential fit of the three points was used to generate the necessary water level *vs.* time data. For the remainder of the tests, more data points were obtained and the additional processing was not required. A capacitance probe (Theta Probe®, ML2x; Thermo Fisher Scientific Inc., Waltham, Massachusetts), which measures the dielectric constant of the soil, was used to indirectly estimate the initial and final soil moisture content of the top six cm of soil in the vicinity of the infiltrometer. A soil specific calibration using several gravimetric soil moisture measurements was also conducted for each rain garden. Bulk density measurements, required to convert gravimetric water content to volumetric water content, were made using the core method (Klute, 1986). Tests in which there was minimal change in water level over ~3-h time period were terminated, suggesting that the K_{sat} value was less than the smallest measured K_{sat} value of 5.6×10^{-7} cm/s. The calculated K_{sat} values for each measurement location were entered into ArcView to provide a map showing the spatial variability in K_{sat} for each rain garden.

The arithmetic mean, geometric mean, and the median were then calculated for each site. Graphs of the cumulative distribution of the measured K_{sat} values along with the theoretical normal and log-normal distributions for the mean and standard deviation (SD) of the data collected were plotted. Visual inspection of the cumulative distribution plots along with the computed coefficient of variation (CV) values was 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 removal of such data points.

The median or mean K_{sat} value from the infiltrometer results; the surface area, A (m^2); and volume, V (m^3) of the water in the rain garden at the time of the test were used to predict the drain time, t, using the following equation:

$$\text{Drain Time} = \frac{V}{K_{sat} A} \tag{2}$$

Equation (2) will provide a rough estimate of the drain time, subject to the following assumptions:

(1) The mean piezometric head over the soil, represented by V/A, is appropriate to estimate drain time, and
(2) The soil is saturated at the conclusion of filling, when drain time measurements commenced.

Synthetic Drawdown Tests

The flow rate needed to fill a rain garden with water for the simulated runoff assessment was calculated to determine if an adequate supply of water was available. The parameters necessary to estimate this flow rate include the surface area of the basin, the estimated or measured infiltration rate, and the storage capacity of the basin. After filling the rain garden with water to the highest level possible, the water level *vs.* time was recorded using a staff gauge and a stop watch. Measurements also were collected every second and averaged over 10 s intervals with an ultrasonic sensor (MassaSonic, M-5000) mounted to a postset at the lowest point in the basin. The time required to fill each rain garden was ~30 min. Measurements of water level began as soon as the inflow was turned off. The reported drain times are based on the actual volume of water used during the synthetic drawdown test and not the maximum capacity of each site.

RESULTS AND DISCUSSION

Visual Inspection

All of the rain gardens contained various species of native perennial vegetation. Four of the sites contained new plantings and were considered to be in good health based on their early stage in development. Four rain gardens suffered from an obvious lack of infiltration observed during a visual inspection, including ponded water, the presence of hydric soils and wetland plants, and a lack of plant growth on compacted soil. These rain gardens failed the Level 1 inspection and will require rehabilitation. Vegetation health at the Cottage Grove (7) 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. With the exception of the four sites determined to be nonfunctional and the Cottage Grove (7) site, the other sites had well-established vegetation that appeared to be healthy.

The results of the inspection of the soils at each rain garden are provided in Table 2. Rain gardens typically have mulch covering the soil surface for moisture and weed control. The topsoil of several rain gardens consisted of a sandy loam soil. Examining the soil profile, as described in the methods section for visual inspection, of the rain gardens is important for the detection of restrictive soil layers that may be present due to improper construction or have formed over time due to prolonged saturation. Soil profiles can give especially useful information as it is possible that a restrictive layer contributes to the desired drain time not being met. At the UM – St. Paul (6) campus rain garden, for example, a lower permeability silt loam soil layer was found to underlay the sandy loam topsoil, which was later found to be an adjustment made during construction. Two other rain garden sites [Thompson Lake (11) and UM – Duluth (12)] had an underlying native soil of finer texture (silt loam and clay) than the overlying topsoil (loamy sand and sandy loam). These two sites were designed with underdrains to compensate for the restrictive layer. The soil profile at the Cottage Grove (7) site consisted of forty inches of sand overlying gravel. The poor retention of water and nutrients in the sandy soil were a potential cause of the failing plants observed during inspection of the vegetation.

Two sets of samples were taken for the UM – Duluth (12) rain garden as it contained two different types of soil. The mean bulk densities of the Cottage Grove (7) rain garden (Table 2) and the coarse sand overlying the underdrain system at the UM – Duluth (12) rain garden were 1.57 and 1.53 g/cm^3, respectively, which are typical values for sand. There was several bulk densities of ~1.0-1.2 g/cm^3, which is indicative of loamy soils and was expected based on the texture of the topsoils in the rain gardens. Sandy soils with a relatively low volume of pores may have a bulk density of ~1.6 g/cm^3, whereas aggregated loams and clay soils fall below 1.2 g/cm^3 (Hillel,

TABLE 2. Summary of the Soil Properties Determined at Each Rain Garden.

ID	Rain Garden Name	Soil Cover	Soil Profile	Soil Color[1]	Bulk Density (g/cm^3)
1	Burnsville	Thick wood mulch	0-31 cm – Sandy loam	10YR 2/2	1.128 ± 0.218 (n = 23)
			31-119 cm – Sand w/large rocks	10YR 3/4	
2	RWMWD #4	Wood mulch	0-38 cm – Sandy loam	5YR 2.5/1	1.323 ± 0.068 (n = 2)
			38-51 cm – Sandy loam	10YR 3/4	
			51-119 cm – Sand	10YR 3/4	
3	A	None	0-15 cm – Silt loam	10YR 3/2	NA
			15-23 cm – Silty clay loam	10YR 4/4	
			23-119 cm – Sand	10YR 4/4	
4	B	None	0-5 cm – Organic matter	Gley 2.5/N	NA
			5-38 cm – Silt loam	10YR 3/2w/red mottles	
			38 cm – Hard surface		
5	RWMWD #5	Wood mulch	0-38 cm – Sandy loam	5YR 2.5/1	1.193 ± 0.163 (n = 8)
			38-51 cm – Sandy loam	10YR 3/4	
			51-119 cm – Sand	10YR 3/4	
6	UM – St. Paul	Wood mulch	0-20 cm – Sandy loam	10YR 2/2	1.182 ± 0.127 (n = 21)
			20-48 cm – Silt loam	10YR 2/1	
			48-119 cm – Sand	10YR 6/4	
			>119 cm – Silt loam w/coarse sand	2.5YR 3/3	
7	Cottage Grove	None	0-76 cm – Sand	10YR 3/2	1.573 ± 0.076 (n = 8)
			76-102 cm – Sand	10YR 4/4	
			102-119 cm – Gravel		
8	C	None	0-6 cm – Organic matter	5Y 2.5/1	NA
			6-18 cm – Sand	10YR 4/3	
			18-28 cm – Sandy clay loam	Gley 4/10Y w/red mottles	
			28-119 cm – Loamy sand w/rocks	5YR 4/3	
9	RWMWD #1	Wood mulch	0-38 cm – Sandy loam	5YR 2.5/1	1.202 ± 0.084 (n = 7)
			38-51 cm – Sandy loam	10YR 3/4	
			51-119 cm – Sand	10YR 3/4	
10	D	None	NA	NA	NA
11	Thompson Lake	Wood mulch	0-13 cm – Loamy sand	10YR 2/2	1.096 ± 0.175 (n = 10)
			13-43 cm – Sand w/rocks	10YR 5/4	
			43-119 cm – Silt loam	10YR 3/1	
12	UM – Duluth	Wood mulch	0-46 cm – Sandy loam	10YR 2/2	0.947 ± 0.106 (n = 8)
			46-117 cm – Clay	5YR 4/4	
			>117 cm – Clay	5YR 4/4 w/gray mottles	

Notes: n, number of samples; RWMWD, Ramsey-Washington Metro Watershed District; UM, University of Minnesota; w/, with.
[1]10YR 2/2 is the notation used to describe the hue, value, and chroma of the soil color (Foth, 1990).

1998). By comparing the bulk density measurements to the texture of the soils, compaction did not appear to be a problem for any of the eight functioning rain gardens.

Infiltration Rate Tests

Infiltration rate tests, using the methods described in the Methods and Analysis section for infiltration rate testing, were performed at the eight functional rain gardens. Rain gardens A (3), B (4), C (8), and D (10) were not included in these tests because they failed the Level 1 assessment based on the existence of hydric soils and wetland plants, therefore infiltration rates were assumed to be poor and/or inhibited at those sites. Six MPD Infiltrometers were used simultaneously allowing infiltration rate testing to be completed within 8 h at each rain garden, with the exception of UM – Duluth (12) due to its large size. The number of locations where measurements were made using the MPD varied among the rain gardens due to differences in rain garden size. The time required for each individual MPD test to be completed ranged from 1.5 min to 8.6 h with an average time of 1.3 h. Only 1% of the tests took 8 h or longer to drain completely, while 78% of the tests were completed in less than 2 h. One percent of the MPD tests were terminated at the UM – St. Paul (6) and UM – Duluth (12) sites due to minimal change in water level over a period of more than 8 h.

The Burnsville (1) rain garden (Figure 2) contained the highest measured K_{sat} value of 8.1×10^{-2} cm/s and the median for the entire rain garden was the second highest of the eight sites. Not surprisingly, the MPD Infiltrometer tests were finished within 15 min at 57% of the locations. The highest measured K_{sat} values were typically near the shrubs and

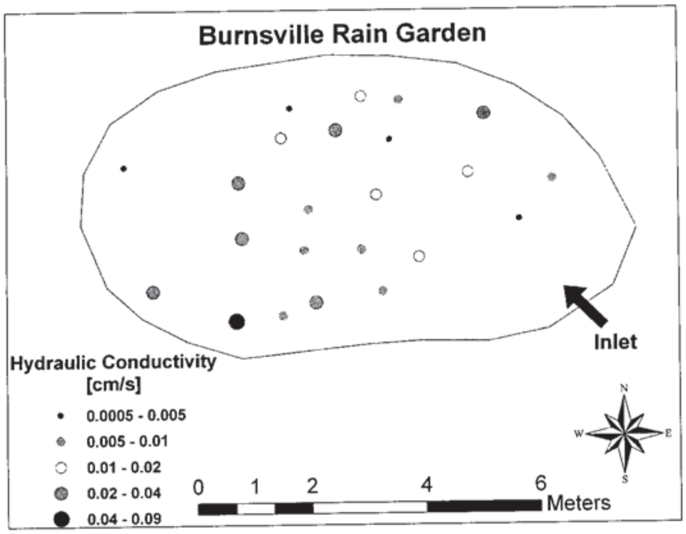

FIGURE 2. Map Showing the Range of K_{sat} Values Measured Using the MPD Infiltrometer at Various Locations Within the Burnsville (1) Rain Garden.

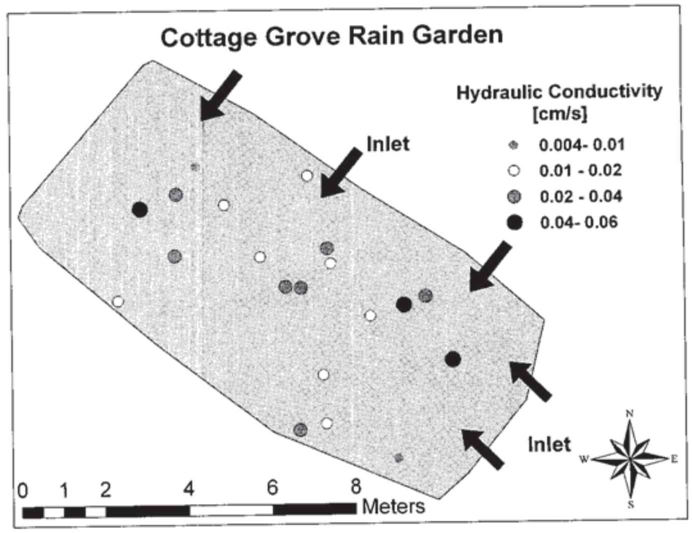

FIGURE 3. Map Showing the Range of K_{sat} Values Measured Using the MPD Infiltrometer at Various Locations Within the Cottage Grove (7) Rain Garden.

grasses. The lowest K_{sat} value (5.5×10^{-4} cm/s) was near the inlet, which could be due to the settling out of eroded clays or from compaction of the surface due to the inflow of runoff. However there was no observed evidence to indicate either scenario. The other low values ($\sim 6 \times 10^{-3}$ cm/s) were randomly located throughout the basin, such that no strong correlation with location in the rain garden could be made at this site for the cause of low infiltration rates. MPD testing could not be performed along the west edge of the basin due to the presence of rocks and dense shrubs.

The Cottage Grove (7) rain garden (Figure 3) contained sandy soils. The distribution of the measured K_{sat} values was close to normal, as indicated by the low CV value (57.4%) and low skewness value (0.91). The sandy soils allowed for rapid infiltration that resulted in 90% of the MPD Infiltrometer tests finishing within 15 min. The higher K_{sat} values ($\geq 2.2 \times 10^{-2}$ cm/s) were located near the failing trees and along the side slopes of the rain garden.

The three rain gardens assessed at the Ramsey-Washington Metro Watershed District (RWMWD) (2, 5, and 9) office are given in Figure 4. RWMWD Rain Garden #1 (9) is the largest of the three rain gardens assessed at this site and had the highest variability in K_{sat} (CV = 94.6%). Four measurements were made in RWMWD Rain Garden #4 (2) due to its small size (29.08 m^2). RWMWD Rain Garden #5 (5) had the highest median K_{sat}, with the lowest values concentrated near the inlet on the south east corner. Accumulation of fine sediment near the inlet and around the sandbags of RWMWD Rain Garden #5 (5) was observed. This is presumed to be the cause of the low infiltration rates near the inlet.

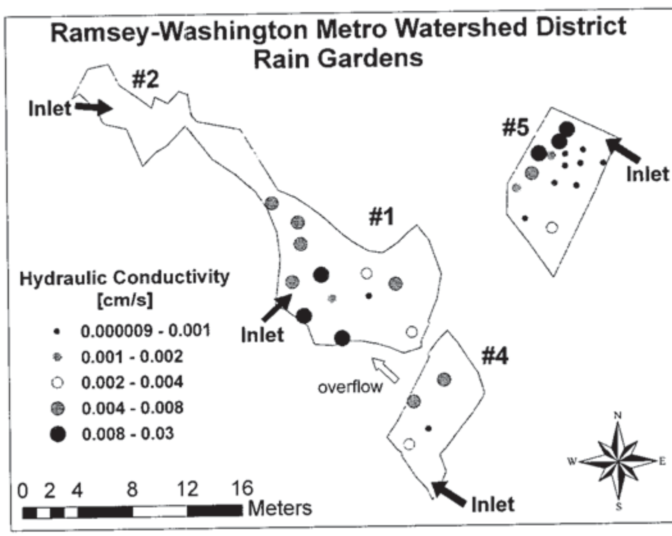

FIGURE 4. Map Showing the Range of K_{sat} Values Measured Using the MPD Infiltrometer at Various Locations Within the RWMWD (2, 5, and 9) Rain Gardens.

As the oldest rain gardens assessed, the Thompson Lake (11) rain garden was more densely covered with vegetation. There were two relatively small curb cut inlets along the west portion of the rain garden receiving stormwater runoff from a parking lot. The highest K_{sat} values (Figure 5) were typically within ~0.5 feet of the perimeter of the large shrubs. The large and dense cover of vegetation may have contributed to the higher K_{sat} values measured at this site. The low K_{sat} values were located in the middle of the rain garden, and may have been caused

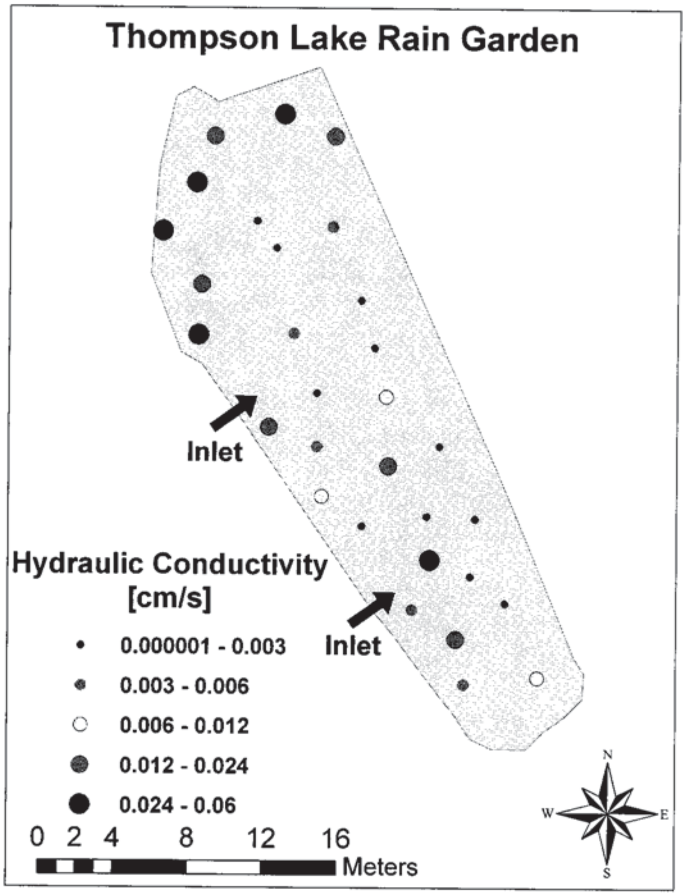

FIGURE 5. Map Showing the Range of K_{sat} Values Measured Using the MPD Infiltrometer Locations Within the Thompson Lake (11) Rain Garden.

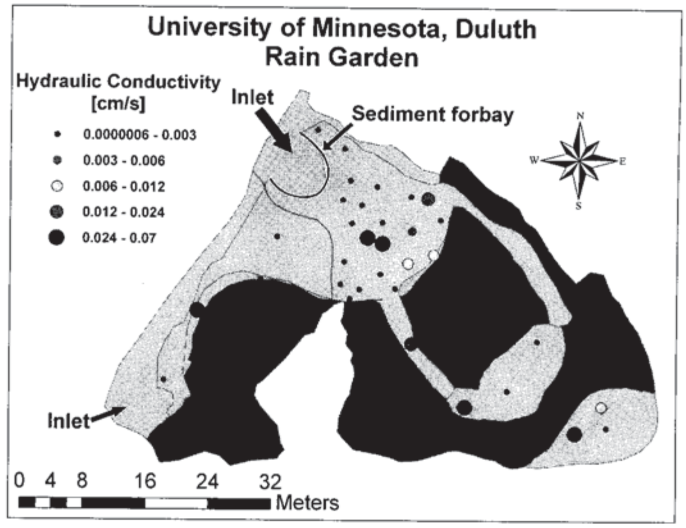

FIGURE 6. Map Showing the Range of K_{sat} Values Measured Using the MPD Infiltrometer at Various Locations Within the UM – Duluth (12) Rain Garden.

by fine solid deposition clogging the macropores connected to the surface; however, this effect was not measured.

The UM – Duluth (12) rain garden (Figure 6) had the greatest variability in the measured K_{sat} values. The rain garden contained two distinct types of soil: coarse sand located directly over an underdrain system and sandy loam overlying clay beneath the vegetated portions of the rain garden. The overall size of this rain garden was 1,350 m^2 which consisted of both upland or woodland zones and rain garden zones. No MPD measurements were made in the woodland zones as the area was at a higher elevation than the rain garden portion. Measurements were concentrated near the inlet of the rain garden and along the pathways of the underdrains. The highest measured K_{sat} values were primarily located on the coarse sand trenches where the underdrains were located. As stormwater enters the rain garden via the sediment forebay, it flows directly to the areas containing the coarse sand and much of it flows downward into the tile drains. The low K_{sat} values ($<2.6 \times 10^{-3}$ cm/s) were primarily in the vicinity of the sediment forebay (northwest corner) and limestone rock riprap inlet in the southwest corner of the rain garden.

At the UM – St. Paul (6) campus rain garden (Figure 7), all of the low K_{sat} values ($<2.9 \times 10^{-3}$ 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 3 h to drain. Overall, 58% of the MPD tests were completed in less than 1 h at this site. The low K_{sat} values found here could be a combination of the restrictive soil layer found at the 20-48 cm depth and clogging of surface soils due to 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 (located just below the north inlet) was terminated because there was no change in the water level over a time period of 3 h.

The distributions of K_{sat} data for each rain garden are shown in Figure 8. Statistical analyses were performed on the measured K_{sat} values and the descriptive statistics including arithmetic mean, geometric mean, median, SD, and CV of K_{sat} for each rain garden were computed and are summarized in Table 3. The variability of K_{sat} was large as indicated by the CV range (57-174%) (Hillel, 1998). Based on the combination of statistical tools utilized, it was determined that a log-normal distribution fit the data best in all cases. It has been observed that field hydraulic conductivity data are often best described by a log-normal distribution (Bjerg *et al.*, 1992; Vauclin *et al.*,

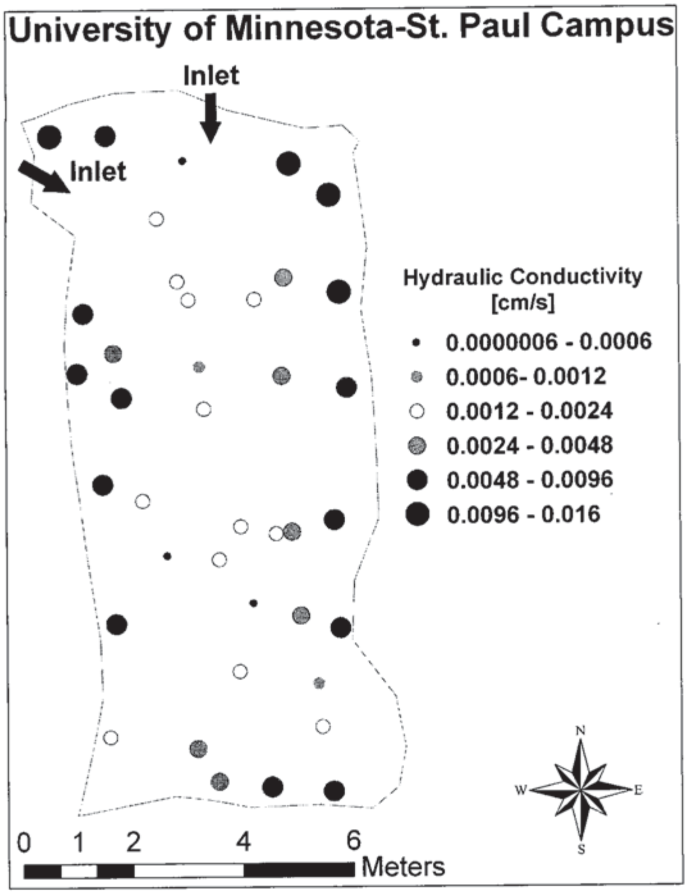

FIGURE 7. Map Showing the Range of K_{sat} Values Measured Using the MPD Infiltrometer at Various Locations Within the UM – St. Paul (6) Rain Garden.

1994; Tsegaye and Hill, 1998; Jang and Liu, 2004; Regalado and Munoz-Carpena, 2004).

Given the distributions of K_{sat}, shown in Table 3 and Figure 8, we can now determine the number of measurements required to accurately estimate the true mean of the K_{sat}. This will provide guidance on selecting the appropriate number of measurements to conduct other experiments or Level 2 assessments. Equation (3) can be used to compute the estimated number of measurements (N) required to be within specified range of the mean ($C.I. - \mu$), where z is the tabulated $z_{\alpha/2}$ value for the desired confidence level of estimation (Klute, 1986).

$$N = \left(\frac{SD \times z_{\alpha/2}}{CI - \mu}\right)^2 \tag{3}$$

The number of measurements (N) that would be necessary to obtain a mean K_{sat} value within selected levels of tolerance (i.e., maximum acceptable difference between the true and computed mean values) was calculated for each rain garden assuming a 95% confidence interval. The results of these calculations along with the actual number of measurements made (N) for each rain garden are shown in Table 4.

Synthetic Drawdown Tests

Three of the sites were evaluated using synthetic drawdown testing (i.e., Level 3). Selection of these sites was based on the size of the rain garden and availability of a water supply. The rain gardens selected for synthetic drawdown testing were Cottage Grove (7), RWMWD #5 (5), and the UM – St. Paul (6) campus. A fire hydrant was used to fill both the RWMWD #5 (5) and UM – St. Paul (6) rain gardens. The Cottage Grove (7) rain garden required the use of a water truck because there was no fire hydrant nearby. The combination of limited volume of water, relatively low delivery flow and high infiltration rate of the soil only allowed the site to be filled to 28% of its estimated maximum capacity. The RWMWD #5 (5) rain garden was filled to 72% of the maximum capacity to prevent overflowing the basin. The UM – St. Paul (6) rain garden was the only site filled to capacity during the synthetic drawdown test. 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 measured drainage times of the three rain gardens are plotted in Figure 9. The Cottage Grove (7), RWMWD #5 (5), and UM – St. Paul (6) rain gardens drained in 0.14, 3.13, and 2.14 h respectively. All three rain gardens drained well before the desired maximum 48-h drainage period, which indicated that the rain gardens were infiltrating water.

The infiltration rate tests were also used to estimate the drain time based on the same initial volume used for each synthetic drawdown test. The appropriate K_{sat} value to estimate drainage time, if the piezometric head difference is assumed to be equal and the low K_{sat} values are spaced uniformly throughout the basin, may be determined by conceptually placing two media of differing K_{sat} next to each other with one piezometric head applied. An application of Darcy's law to the flow through these two media results in an overall flow that is dependent upon the arithmetic mean of the two K_{sat} values. The drain time is thus proportional to the inverse of the arithmetic mean of the K_{sat} values. The drain times computed using the arithmetic mean K_{sat} values for all three rain gardens, however, were lower than the corresponding synthetic drawdown test drain times (Figure 9). It is believed that the location of the higher K_{sat} values around the perimeter of the basins influenced the spatially averaged, arithmetic mean to a

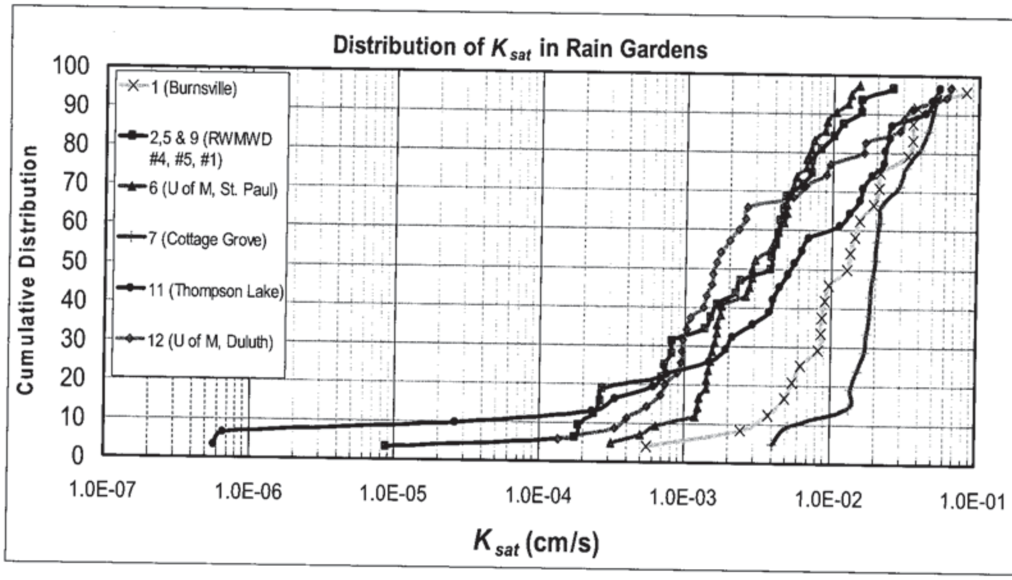

FIGURE 8. Distribution of Measured K_{sat} Values for Eight Rain Gardens. Note that the three rain gardens at the RWMWD (2, 5, and 9) site were combined into one dataset for the plot.

TABLE 3. Statistics for Measured K_{sat} Values From Eight Rain Gardens.

Statistical Parameter	1 (Burnsville)	2 (RWMWD #4)	5 (RWMWD #5)	6 (UM – St. Paul)	7 (Cottage Grove)	9 (RWMWD #1)	11 (Thompson Lake)	12 (UM – Duluth)
Number of measurements	23	4	15	41	20	12	30	34
Arithmetic mean (cm/s)	1.8×10^{-2}	3.2×10^{-3}	3.3×10^{-3}	4.3×10^{-3}	2.4×10^{-2}	7.5×10^{-3}	1.2×10^{-2}	9.1×10^{-3}
Geometric mean (cm/s)	1.1×10^{-2}	9.0×10^{-4}	1.2×10^{-3}	2.3×10^{-3}	2.0×10^{-2}	5.1×10^{-3}	2.7×10^{-3}	2.0×10^{-3}
Median (cm/s)	1.3×10^{-2}	4.0×10^{-3}	8.1×10^{-4}	2.9×10^{-3}	2.0×10^{-2}	5.4×10^{-3}	5.3×10^{-3}	1.6×10^{-3}
SD (cm/s)	1.8×10^{-2}	2.1×10^{-3}	4.9×10^{-3}	3.8×10^{-3}	1.4×10^{-2}	7.1×10^{-3}	1.5×10^{-2}	1.6×10^{-2}
CV (%)	100	67.4	148	87.7	57.4	94.6	123	178
Min. (cm/s)	5.5×10^{-4}	1.0×10^{-5}	1.8×10^{-4}	$<7.0 \times 10^{-7}$	4.0×10^{-3}	8.2×10^{-4}	7.0×10^{-7}	$<7.0 \times 10^{-7}$
Max. (cm/s)	8.1×10^{-2}	4.7×10^{-3}	1.6×10^{-2}	1.5×10^{-2}	5.4×10^{-2}	2.6×10^{-2}	5.4×10^{-2}	6.4×10^{-2}
Range (cm/s)	8.1×10^{-2}	4.7×10^{-3}	1.6×10^{-2}	1.5×10^{-2}	5.0×10^{-2}	2.5×10^{-2}	5.4×10^{-2}	6.4×10^{-2}

Notes: CV, coefficient of variation (CV = SD/Mean); RWMWD, Ramsey-Washington Metro Watershed District; SD, standard deviation; UM, University of Minnesota.

greater extent than they influenced drainage time. As the drainage progresses, the region around the perimeter of the basin would no longer remove pooled water because of its higher elevation.

The median and geometric mean K_{sat} values obtained from the infiltration rate tests were also used to predict the drain times for comparison with the measured values from the synthetic drawdown tests (based on the same initial test volumes). The predicted drain times based on the median K_{sat} value and geometric mean K_{sat} value at RWMWD #5 (5) were both in better agreement with the observed drain time than the predicted drain time based on the mean K_{sat} value. The same is true for the Cottage Grove (7) site, although the predicted and measured drain time times were all very brief. The UM – St. Paul (6) rain garden drain times predicted from the median and geometric mean K_{sat} values were in slightly better agreement with the measured drain time than the predicted drain time based on the mean K_{sat} value. The large differences between the predicted and measured drain times for the UM – St. Paul (6) rain garden are likely due to the influence of the restrictive soil layer on drainage when the rain garden is filled to capacity during synthetic drawdown testing. The MPD Infiltrometer tests infiltration rates in the upper 15-20 cm. The limiting soil layer would thus not be a factor because of the small

TABLE 4. Estimated Number of Measurements Required to Obtain a Mean K_{sat} Value That Is Within 5, 10, and 15% of the True Mean 95% of the Time and Comparison With the Actual Number of Measurements Made (*N*).

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

Notes: RWMWD, Ramsey-Washington Metro Watershed District; UM, University of Minnesota.

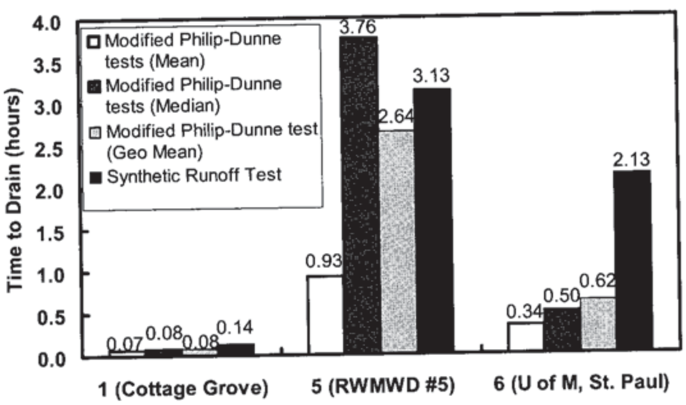

FIGURE 9. Comparison of Measured Drain Times Obtained From Synthetic Runoff Tests With Drain Times Estimated Using the Mean, Median, and Geometric Mean K_{sat} Values From MPD Infiltrometer Tests.

volume of water used in these tests and the ability for the water to flow laterally. The synthetic drawdown test determines drainage time for the upper 40-100 cm, depending upon the depth of water placed into the basin. The soil profile results from the visual inspection of this rain garden were useful in explaining the discrepancy.

CONCLUSIONS

Three new approaches for assessing the performance of rain gardens and other infiltration stormwater BMPs were developed and evaluated: visual inspection (Level 1), infiltration rate testing (Level 2), and synthetic drawdown testing (Level 3).

All three assessment approaches provided useful information regarding the overall function of rain gardens. Visual inspection of the vegetation and soils provided a preliminary indication of the ability of the rain garden to infiltrate stormwater runoff. Infiltration rate testing provided information on the spatial variability in K_{sat} and an estimate of the overall drain time of the rain garden. This information is useful for identifying specific locations to target for maintenance, which should improve performance and may prolong the life of the rain garden, and reduce costs overall. Infiltration rate testing can also be used 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. The combination of visual inspection and infiltration rate testing is particularly useful for assisting in the development of maintenance tasks and schedules. While infiltration rate testing has numerous benefits, this method only provides a rough estimate of the time required for the rain garden to drain, especially when relatively permeable surface soil layers are underlain by restrictive soil layers. The synthetic drawdown test can be used to measure the drainage time quickly and with little effort when water supply is available to fill the basin sufficiently to determine a drainage time, which restricts the tests to rain gardens smaller than roughly 80 m^2 in plan area.

A multilevel assessment approach allows for the identification of problems in rain gardens, potential causes, and possible solutions. Nevertheless, when there are a large number of rain gardens to evaluate and a multilevel assessment of each rain garden is not feasible, assessment by visual inspection should be done periodically (e.g., annually) to identify potential problems that may impair rain garden performance.

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