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Design and Construction of Infiltration Facilities

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Infiltration stormwater control measures are an important structural practice to mitigate the impacts of urbanization on stormwater quality and quantity. Infiltration stormwater control measures help to mimic the natural processes of infiltration and evapotranspiration. Unfortunately, the failure rate of infiltration stormwater control measures has been observed to be between 10% and 50%. Two common causes of failure are addressed in this work, namely improper siting and improper characterization of saturated hydraulic conductivity. A procedure to calculate a preliminary infiltration rating (PIR) was developed in a geographic information system to identify areas where infiltration stormwater control measures are likely to be successful. The Modified Philip-Dunne infiltrometer, double ring infiltrometer, Turf-Tec IN2-W infiltrometer, and soil texture analysis were used to estimate infiltration capacity in three swales in the Twin Cities Metropolitan area. A correction factor was proposed for the Turf-Tec IN2-W infiltrometer. A protocol for assessing infiltration capacity was also proposed.

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DESIGN AND CONSTRUCTION OF INFILTRATION FACILITIES

FINAL REPORT

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LIST OF ABBREVIATIONS

ArcMap: Esri ArcMap v10.5.1

ASTM: American Society for Testing and Materials

cm: centimeter

cm/hr: centimeter per hour

DRI: double ring infiltrometer

ft: feet

GIS: geographic information system

GSD: geometric standard deviation

in: inch

in/hr: inch per hour

K_{sat}: saturated hydraulic conductivity

mm: millimeter

mm/hr: millimeter per hour

MPD: Modified Philip-Dunne infiltrometer

PIR: Preliminary Infiltration Rating

SCMs: stormwater control measures

SD: standard deviation

ST: soil texture method of identifying infiltration rate

TT: Turf-Tec IN2-W infiltrometer

EXECUTIVE SUMMARY

Infiltration stormwater control measures (SCMs) are an important structural practice used to mitigate the stormwater quantity and quality impacts of land development. Impervious surfaces generate more surface runoff that reaches receiving waters rapidly relative to undeveloped, pervious surfaces. These same impervious surfaces also contribute a pollutant loading that adversely impacts water quality. Infiltration SCMs attempt to mimic natural hydrologic processes by slowing surface runoff and increasing the fraction that infiltrates into the subsurface or is evapotranspired. Unfortunately, a relatively high failure rate, in the range of 10% to 50%, has been observed in infiltration SCMs. There are many factors contributing to this high failure rate, but two primary reasons are improper site selection and the need for improved methods to estimate the infiltration capacity of a site. Interviews with practitioners identified a need for siting potential infiltration areas early in the scoping process. Practitioners also indicated that pre-design infiltration rates were typically determined based on soil texture rather than in-situ infiltration measurements. The focus of this research is to provide practitioners tools that would assist in identifying sites likely to be successful prior to field investigation, and guidance on how to conduct a field investigation to assess the in-situ infiltration rates. Selection of an appropriate site can alleviate issues related to the soil profile and groundwater interactions. In-situ infiltration measurements can verify that the infiltration capacity is sufficient.

A rapid screening tool was developed in a geographic information system (GIS) to consistently evaluate the likely infiltration potential of a project area. The preliminary infiltration rating (PIR) aggregates four variables that are critical to infiltration SCM success into a composite rating. These variables are available online with broad geographic coverage and include: (1) saturated hydraulic conductivity (K_{sat}), (2) depth to groundwater, (3) topographic slope, and (4) relative elevation. The PIR can be displayed as a “heat map” of the infiltration potential of a project area. Information related to environmentally sensitive areas, property information, proposed infrastructure, and other data can be overlaid on the PIR to assist in identifying areas likely to be suitable for infiltration SCMs. The PIR aggregation method was calibrated and validated using the Anoka Conservation District’s rain garden maintenance data set. The PIR was found to have a correct or conservative rating for 85% of rain gardens, indicating that an infiltration SCM is likely to perform as well or better than predicted by the PIR.

Another aspect of the report is guidance on conducting a field investigation to assess the in-situ infiltration rates. Four methods of evaluating in-situ infiltration capacity were implemented in three swales in the Minneapolis-Saint Paul metropolitan area. These methods include the Modified Philip-Dunne infiltrometer, the double ring infiltrometer, the Turf-Tec infiltrometer, and soil texture analysis. The variability captured by each method was evaluated. Soil texture analysis was found to underestimate the infiltration capacity relative to the other methods. The heterogeneity of the soil infiltration capacity was not captured by the soil texture analysis, whereas it was apparent in the three in-situ measurement methods.

Saturated hydraulic conductivity is highly heterogeneous property in both natural soils and relatively homogeneous engineered media. Therefore, numerous infiltration measurements are required to characterize the infiltration capacity of an area. Saturated hydraulic conductivity has been found to follow a log-normal distribution, requiring adaption of statistical methods that assume normality. A method is proposed to calculate the required number of measurements as a function of the allowable error, required level of confidence, and spread of the data.

The Turf-Tec IN2-W infiltrometer has historically been used in the turf management industry with limited usage in engineering applications. The device is small, easy to use, simple to understand, and requires a minimal water volume creating interest in adopting the device if the accuracy can be quantified. Laterally divergent flow violates the one-dimensional flow assumption creating a non-conservative error. The Turf-Tec measurements collected in swales and identified in numerical simulations were compared to the double ring infiltrometer measurements. In the swales, the Turf-Tec overestimated the infiltration rate relative to the DRI by a factor ranging from 2.2 to 3.9. In numerical simulations on sand, loamy sand, and sandy loam, the TT tended to overestimate the double ring infiltrometer infiltration rate by a factor of 1.8 to 2.5 and overestimate the true K_{sat} by a factor from 2.2 to 3. Reducing the Turf-Tec field measurements by a factor of 3 may be a conservative method of estimating the infiltration rate in sands, loamy sands, and sandy loams typical of infiltration SCMs and engineered media. The systemic error in the Turf-Tec increases substantially in finer soil textures. Therefore, the Turf-Tec should be considered qualitative in fine soils with use limited to comparative purposes.

A protocol was developed for assessing the infiltration potential of a site based on the completed in-situ infiltration measurements. The protocol describes selecting an appropriate infiltration measurement method, estimating an adequate number of measurements based on the guidance provided herein, locating the measurements within a project area, and applying specified procedures at the site. The protocol discusses evaluating the measurements individually and a method to aggregate the results into a site-specific effective saturated hydraulic conductivity.

This research is applicable to projects in transportation, municipal engineering, site development, and other land disturbing activities. The PIR can be used to identify potential locations for an infiltration SCM early in the planning or design phase and can be used to communicate those decisions between stakeholders. The infiltration measurement protocol can be used with the field method of choice to verify the infiltration potential during the site investigation. The infiltration measurement protocol can also provide guidance during construction quality control and post-construction maintenance. This research will benefit Minnesota by providing guidance that can reduce the failure rate of infiltration SCMs while mitigating the impacts of urbanization on stormwater quality and runoff volumes.

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

Infiltration stormwater control measures (SCMs) are an important structural practice to mitigate the stormwater quantity and quality impacts of land development. Runoff from impervious surfaces creates a substantial disturbance to natural hydrologic processes. Impervious surfaces generate more surface runoff that reaches receiving waters rapidly relative to undeveloped, pervious surfaces. These same impervious surfaces also contribute a pollutant loading that adversely impacts water quality. Infiltration SCMs attempt to mimic the natural hydrologic function by slowing surface runoff and increasing the fraction that infiltrates into the subsurface or is evapotranspired. Infiltration SCMs include a variety of different structural practices such as infiltration basins, infiltration trenches, bio-infiltration basins, rain gardens, bio-infiltration swales, and subsurface infiltration systems.

Infiltration is defined as the flow of water through the soils surface at the air-soil boundary. Permeability is defined as the ability of the soil mass to pass water within its body. Permeability and infiltration are quantified by hydraulic conductivity, which has units of length per time and measures how easily water can pass through soil.

Unfortunately a relatively high failure rate has been observed in infiltration SCMs, in the range of 10% to 50% (Bean & Dukes, 2016; CTC & Associates LLC, 2018; Hilding, 1994; Lindsey, Roberts, & Page, 1992). There are numerous factors that may contribute to this high failure rate including improper siting, low saturated hydraulic conductivity soils in the soil profile, groundwater mounding, sedimentation, and compaction during construction (CTC & Associates LLC, 2018). Of these factors, low hydraulic conductivity soils and compaction during construction are common reasons for initial failure to adequately infiltrate water. Selection of an appropriate site can alleviate issues related to the soil profile and groundwater interactions. Infiltration measurements before, during, and post-construction can verify that the infiltration capacity is not affected by sedimentation or compaction, either from construction practices or pollutants in the stormwater loading. This research focused on providing tools that assist in identifying an appropriate site prior to field investigation and methods to measure the infiltration capacity throughout the construction and life of the infiltration SCM.

1.2 LITERATURE REVIEW

The Minnesota Pollution Control Agency (MPCA) Construction Stormwater General Permit requires that a volume reduction practice, such as infiltration SCMs, be the first consideration in a permanent stormwater treatment system when greater than 1 acre of new impervious surface is proposed (Minnesota Pollution Control Agency, 2018). States vary significantly in their guidance for the testing and design of infiltration SCMs. The variation in guidance between states is assumed here to indicate that a consensus on the most appropriate methods has not been achieved. Some of the areas where variation in guidance exists includes the number and type of infiltration tests, whether soil texture is allowable for estimating saturated hydraulic conductivity (K_{sat}), the range of allowable K_{sat}, the required factor of safety on field measured K_{sat}, the required maximum drawdown times, the allowable depth of active storage, and the recommended catchment area ratio limits.

1.2.1 Number and Type of Infiltration Tests

States vary in their preferred or required field measurement method and number of tests, as the following examples illustrate. Pennsylvania requires a minimum of 1 field test with preference for a double ring infiltrometer (Pennsylvania Department of Environmental Protection, 2006). North Carolina requires 2 field tests for SCMs between 2,000 and 20,000 square feet then 1 additional test for every additional 10,000 SF, with preference for a double ring infiltrometer (North Carolina Department of Environmental Quality, n.d.). Minnesota allows the designer to choose between infiltrometer tests, permeameter tests, or pit tests and requires 2 infiltration tests for a SCM between 1000 and 5000 square feet, with 1 additional test for every additional 5000 square feet, unless the first test yields an infiltration rate in excess of 2 inches per hour (Minnesota Pollution Control Agency, 2017a). Maryland requires 1 field infiltration test for every 200 square feet of SCM, requiring a downhole percolation test using a solid casing (Center for Watershed Protection and Maryland Department of the Environment Water Management Administration, 2009).

1.2.2 Allowed Use of Soil Texture

Some states including Minnesota (Minnesota Pollution Control Agency, 2017a) allow infiltration rates to be based on soil texture, generally referring back to Rawls, W.J., Gimenez, D., & Grossman, R., (1998). Western Washington allows infiltration rates to be calculated based on grain size in accordance with Massman, Butchart, & Stolar (2003). However, the variability of K_{sat} within a soil texture group can exceed the variations between soil texture groups, and hydrologic soil group may be a more accurate method of predicting K_{sat} from soil properties (Lee, Traver, & Welker, 2016).

1.2.3 Range of Allowable K_{sat}

States vary in their required minimum and maximum values of K_{sat}. Minimum K_{sat} values are generally intended to ensure that infiltration is feasible and hydric conditions do not develop. Minimum K_{sat} values for infiltration practices typically range from 0.2 in/hr in Minnesota to 0.6 in/hr in Wisconsin (Minnesota Pollution Control Agency, 2017a; Wisconsin Department of Natural Resources, 2017). Maximum K_{sat} values are intended to slow the rate of infiltration to promote pollutant attenuation. Maximum measured K_{sat} values, where states have a maximum allowable value, are typically in the range of 8.3 - 10 in/hr (Minnesota Pollution Control Agency, 2017a; Pennsylvania Department of Environmental Protection, 2006). The case for a maximum infiltration rate has, to our knowledge, not been well documented. We believe that it is related to the maximum filtration rates for stormwater filters to allow sufficient time for pollutant filtering, where filtered stormwater is discharged from the SCM into a storm sewer. The same point made for an infiltration practice does not factor in the impact of the soil under the infiltration practice on constituent concentration.

1.2.4 Factor of Safety on Field Measured K_{sat}

A factor of safety is generally required on field tested K_{sat} rates for use in design. The factor of safety is used to reduce the estimate of K_{sat} to account for natural soil heterogeneity and long-term reduction of infiltration rate from clogging. States commonly recommend a factor of safety in the range of 2-3. Western Washington varies the factor of safety based on type of test, number of tests, and site variability in the range of 1.5 to 8.4 (Washington State Department of Ecology, 2014). The scientific basis for a choice of the factor of safety has not been established in the literature.

1.2.5 Required Drawdown Times

A maximum drawdown time is specified to promote longevity of the upland landscaping within the SCM and to ensure there will be available storage volume in the event of multiple storms occurring within a close timeframe. For example, Wisconsin limits the maximum drawdown time to 24 hours (Wisconsin Department of Natural Resources, 2004). Minnesota limits the maximum drawdown time to 48 hours (Minnesota Pollution Control Agency, 2017a). North Carolina limits the maximum drawdown time to 72 hours (North Carolina Department of Environmental Quality, n.d.). A maximum drawdown time of 48 to 72 hours is common to support survival of the upland plants typical of surface infiltration SCMs.

1.2.6 Allowable Depth of Active Storage

Limiting the depth of active storage can promote growth of the upland landscaping typical of infiltration SCMs, promote safety by eliminating deep pools of standing water, and prevent compaction due to excess weight of water on the native soil interface. Larger active storage depths allow developers to utilize a smaller footprint when soils have a high infiltration capacity. Minnesota limits the depth of active storage to 1.5 feet for bioinfiltration basins, but allows up to 6.5 feet of active storage in infiltration basins (Minnesota Pollution Control Agency, 2017a). Most other state recommendations fall within this range.

1.2.7 Recommended Catchment Area

Variations exist between states in recommended maximum catchment areas and the ratio of catchment area to infiltration area. Limiting the catchment area is intended to reduce maintenance issues, extend the life of the infiltration SCM, and prevent issues with groundwater mounding. Pennsylvania recommends limiting the catchment area to the infiltration surface area ratio to 5:1 (Pennsylvania Department of Environmental Protection, 2006). Maryland recommends a maximum of 10 acres catchment to an infiltration basin (Center for Watershed Protection and Maryland Department of the Environment Water Management Administration, 2009). Wisconsin recommends limiting the catchment area to a bioinfiltration basin to 2 acres but allows up to a 50 acre catchment area for an infiltration basin (Wisconsin Department of Natural Resources, 2004, 2014). Minnesota recommends limiting the catchment area to a bioinfiltration basin to 5 acres while allowing up to a 50 acre catchment area to an infiltration basin with a maximum 5:1 ratio of impervious area to infiltration area (Minnesota Pollution

Control Agency, 2017a). Information on how these maximum catchment areas or catchment area ratios were selected has not been found in the literature.

1.2.8 Determination of Saturated Hydraulic Conductivity

The K_{sat} is a key parameter that controls the rate of infiltration and influences the size, location, and drawdown rate of the infiltration SCM. Numerous field and laboratory methods exist to calculate K_{sat} including pits, permeameters, infiltrometers, column tests, and flood tests. Variation of measured K_{sat} between tests of the same type at the same location, between testing methods at the same location, and spatial variability of K_{sat} within the same soil type can be significant. Rawls et al., (1998) found the 25th and 75th percentile K_{sat} values for soils within the same texture class could vary from the geometric mean by a factor of 1.2 to 5.8.

Johnson (1963) suggests measurements should use the largest ring practicable to avoid divergent flows, and recommends maintaining a constant head for 6 hours in a double ring configuration using a 12-inch inner ring and 24-inch outer ring. Bouwer (1986) identified that flow below a cylindrical infiltrometer is not vertical but diverges laterally, causing an overestimation of the vertical infiltration rate. The magnitude of the error was suggested to be proportional to the ratio of the cylinder diameter to the unsaturated pressure head of the soil adjacent to the infiltrometer. Cylinder infiltrometers with a diameter exceeding 3 feet (1 meter) are recommended.

Zukowski et al., (2016) compared the geometric mean from a series of tests on an infiltration basin to the basin wide measured infiltration rate. This study used 7 single ring infiltrometer tests and found the geometric mean was within an order of magnitude of the basin wide infiltration rate and more accurate than any single test, suggesting that multiple tests are necessary to characterize spatial heterogeneity.

Normal seasonal variations in K_{sat} occur due in part to fluctuations in temperature that effect the viscosity of water, surface tension of water, changes in the diffuse double layer thickness of the clay content of the soil, and possibly other factors (Constantz, 1982). A study of 2 infiltration SCMs measured variations of ponded water depth with time over 2 and 4 years, respectively, found K_{sat} may vary by a factor of 2 within a typical year as a result of the temperature dependency of water viscosity of water as well as other, unidentified factors (Emerson & Traver, 2008).

Infiltration rate testing during and immediately following the construction of an infiltration SCM has the potential to identify issues early in the construction process. Le Coustumer et al. (2009) found that initial estimate of K_{sat} was the only statistically significant explanatory variable of long-term hydraulic conductivity, when other variables considered include age of the SCM, SCM size, catchment size, volume of water received per year, and total volume of water received per area of SCM since construction.

Long-term infiltration monitoring has shown that properly designed, constructed, and maintained SCMs have been able to maintain design capacity. Paus et al., (2014) found that 3 bioinfiltration practices had an increase in K_{sat} over four years, along with a decrease in bulk density of the media and an increase in vegetative cover. Kluge et al. (2018) studied 22 bioretention swales in operation for 11-22 years using double ring infiltrometer tests and found only 8% of tests indicating an infiltration rate lower than the current design recommendations, although infiltration rates used in design or measured immediately post-construction were not available. In contrast, a case study of an underground infiltration trench that had not been maintained indicated a decline in infiltration capacity over a 15 year service life (Bergman et al., 2010). Le Coustumer et al., (2012) conducted a large-scale laboratory study of 15 different biofilter configurations and found the average K_{sat} decreased to 27% of the initial value over 72 weeks of operation. Vegetation has been shown to play a critical role in preventing clogging of the soil surface (Gonzalez-Merchan et al., 2012). The lack of vegetation in underground infiltration SCMs may increase the maintenance requirement and reduce the longevity relative to vegetated surface infiltration SCMs due to the clogging of pores with fine sediment and no root structure to maintain the porosity.

1.3 INTERVIEWS WITH PRACTITIONERS

Interviews were conducted with individuals currently working in relevant areas to gain an understanding of the current practices as a supplement to the literature review. Additionally, the interviews were intended to identify knowledge or resource gaps, if any existed. A total of 5 interviews were conducted between August 2018 and February 2019. A summary of the interviews including the participants is included Table 1.1. The majority of the interviews focused on each interviewee's recent experience with a representative case study project and discussed how the stormwater management requirements were identified and satisfied for that case study project.

Table 1.1 Summary of Conducted Interviews

Date of Interview	*Participant Affiliation*	*Participant Name(s)*	*Case Study Project*
August 20, 2018	MnDOT District 8	Allen Schmitz (Schmitz, 2018)	TH-71 State Project No: 3417-18
August 24, 2018	MnDOT District 7	Scott Morgan and Chuck Slama (Morgan & Slama, 2018)	TH-60 State Project No: 1703-69
August 31, 2018	MnDOT District 1	Dave Mohar and Dan Squires (Mohar & Squires, 2018)	TH-1 State Project No: 6904-46
October 18, 2018	Consulting firms	Craig Johnson (RANI Engineering) and Justin Klabo (AE2S) (C. Johnson & Klabo, 2018)	TH-610 State Project No: 2771-37
February 6, 2019	MnDOT Metro District	Beth Neuendorf and Dave Bauer (Neuendorf & Bauer, 2019)	n/a

There were several consistent, recurring themes that were discussed in multiple interviews. These included design preferences, design processes, quality-control techniques, and general ideas for improvements to implementing stormwater infiltration practices. The recurring themes were:

- There was a strong emphasis on identifying potential infiltration areas early in the scoping process. Then site specific testing would be completed with an effort not to change basin locations later in the project. If site specific testing yielded undesirable results for infiltration, the preference was for converting the infiltration basin to a filtration basin rather than trying to relocate the basin.
- There was a preference for using filtration basins over infiltration basins if the soils were not completely ideal for infiltration. This concern was based around mitigating the risk of needing a design change during construction and trying to ensure the long-term water quality performance of the basin.
- In most instances, infiltration basins were installed with a capped backup underdrain. The cost of an underdrain installed while the contractor was on-site during original construction was generally considered small being it provided insurance the basin could function as a filtration basin if necessary.
- Infiltration rates are generally determined by soil texture during the design phase of the project. Post-construction verification of infiltration rates with a double ring infiltrometer was common.
- The maximum ponding depth of infiltration SCMs was typically limited to approximately 2 feet. This maximum depth was determined with consideration to safety concerns, concerns related to vegetation health, and concerns about the geotechnical stability of the earthen berms that create the infiltration basin.
- Easy rule of thumb calculations that could be used prior to any site-specific investigation were thought to be beneficial.
- It was suggested that adding a water quality credit process to the MPCA permit would be beneficial. This would allow regional treatment options to be considered as mitigation for increases in impervious surface in a specific project. The idea was that the water quality budget could be spent where the impact would be most beneficial, even if that area were not within the project limits or the right of way.

1.4 OBJECTIVES

The objective of this research is to provide practicing engineers with applicable tools to increase the success rate of implementing infiltration SCMs. The guidance will focus on two key components of implementation: (1) identifying a site that is likely suitable for constructing an infiltration SCM using a desktop analysis, and (2) characterizing the saturated hydraulic conductivity of a site. Identifying a suitable site can alleviate issues related to low hydraulic conductivity soils in the profile or adverse interactions with the groundwater. Identifying a suitable site prior to field investigation can save time and resources by limiting the scope, as it would be impracticable to conduct a detailed field investigation throughout a large area. Saturated hydraulic conductivity is highly heterogeneous spatially and temporally and will likely change throughout the normal life cycle of an infiltration SCM. It is therefore critical to characterize methods used to quantify the K_{sat} during design, to be able to verify during construction, and to be able to monitor post-construction to ensure successful implementation over the life cycle of the infiltration SCM.

This report contains sections that address each of the key objectives. Chapter 2 will discuss a GIS-based desktop analysis approach developed for identifying sites likely suitable for a surface infiltration SCM. Chapter 3 will evaluate various point infiltration measurement methods. Chapter 4 will focus on calibrating a small, rapid infiltration measurement method relative to more established methods. Chapter 5 will use the findings of Chapter 3 and Chapter 4 to develop an implementable field protocol for assessing saturated hydraulic conductivity. Finally, Chapter 6 will include a discussion of the benefits and limitations, as well as the conclusions of this research.

CHAPTER 2: RAPID PRE-DESIGN SCREENING TOOL

2.1 GIS METHODS AND SOURCES

The purpose of Chapter 2 is to provide engineering designers and planners with a rapid screening tool to identify sites where infiltration SCMs are likely to be successful, that can be used before or early in the design process. This tool can be used to guide the site-specific field investigation and may serve as a communication tool between engineers, developers, landowners, and regulators including those with non-technical backgrounds. Identifying appropriate sites early in the design process allows infiltration based SCMs to be proactively incorporated into the development plan. Automating the process by identifying the critical datasets and compiling the data into a composite rating can save time and produce consistent results. Details are discussed herein and published in Tecca et al., (2021b).

There is limited research providing example assessment systems that use spatial data to identify areas with the potential to support managed aquifer recharge (MAR). Ghayoumian et al., (2007) proposed a fuzzy logic product operator such that a non-favorable variable would have a small rating and therefore a large influence on the overall rating. It was proposed that the MAR potential should be evaluated based on the soil infiltration rate, topographic slope, dry alluvial thickness, and electrical conductivity. Electrical conductivity was used to quantify groundwater salinity, which is most applicable in coastal regions where water recovery for reuse is intended. Direct surface recharge basins were the method selected to achieve the MAR goals, and these operate very similar to many infiltration SCMs.

Miller (2014) completed a GIS based analysis for use in soil mapping that calculated relative elevation and validated the procedure with the field assessment of soil scientists. The relative elevation describes the position of a point on the hillslope where larger positive values indicate areas closer to the top of a local hill and larger magnitude negative values indicate areas closer to a local depression. The proposed relative elevation was calculated as a function of the elevation at a point and the maximum and minimum elevations within a neighborhood of 443 feet (135 meters) of the point of interest. The 443-foot (135 meter) neighborhood was identified by Miller (2014) as the optimal analysis scale for relative elevation by validating the GIS calculation with field observations by a soil scientist.

The geographic information system (GIS) analysis is implemented herein using Esri ArcMap v10.5.1 (ArcMap). The ArcMap software was selected as it is commonly used by industry professionals and allows a user to overlay additional information, if necessary. The ModelBuilder application within ArcMap was used to implement the workflow.

Construction projects in Minnesota that add more than 1 acre of new impervious surface area are required to treat a water quality volume equal to 1-inch times the new impervious surface in accordance with the MPCA Construction Stormwater General Permit (Minnesota Pollution Control Agency, 2018). Section 15.5 of the General Permit requires that a volume reduction practice such as an infiltration SCM be considered first. The General Permit identifies certain areas where infiltration SCMs are prohibited, but it does not provide guidance on identifying where infiltration SCMs are likely to be successful. Areas where infiltration is prohibited in the General Permit are generally summarized in the following list (numbers indicate the section of the General Permit).

1. 16.3 – any wetland areas
2. 16.14 – run-on from vehicle fueling areas cannot be infiltrated
3. 16.15 – areas of contaminated soil
4. 16.16 – areas where soil infiltration rates exceed 8.3 inches per hour
5. 16.17 – areas with shallow groundwater or shallow bedrock (minimum 3-feet of separation)
6. 16.18 – areas where soils are included in Hydrologic Soil Group D
7. 16.19 – drinking water Emergency Response Areas (ERA) and Drinking Water Supply Management Areas (DWMSA), in accordance with the following:
    a. In an ERA that is within a high or very high vulnerability DWSMA
    b. In an ERA that is within a moderate vulnerability DWSMA unless a higher level of engineering review is completed and approved
    c. Outside an ERA but within a high or very high vulnerability DWSMA unless a higher level of engineering review is completed and approved
8. 16.20 – within 1000 feet upgradient or 100 feet downgradient of active karst features
9. 16.21 – run-on from industrial facilities cannot be infiltrated

Of the 9 prohibitions, 6 of the criteria have readily available GIS data within the State of Minnesota: wetlands, contaminated soils, shallow groundwater or bedrock, hydrologic soil group, Drinking Water Emergency Response Areas, Drinking Water Supply Management Areas, and karst features. It is recommended that the available data is reviewed for a specific project and the areas where infiltration is likely prohibited are aggregated into a prohibition layer within a GIS software. A summary of the data sources used to identify areas where infiltration is likely to be successful and likely to be prohibited is provided in Table 2.1.

The prohibitions of run-on from vehicle fueling areas (16.14) and industrial facilities (16.21) relate to the areas that are included in the infiltration catchment area, not the location of the infiltration facility itself. For these facilities, it would be the responsibility of the designer to segregate the stormwater generated in these prohibited areas through appropriate grading or storm sewer piping to ensure the stormwater is treated as required by the applicable permits and not directed towards the infiltration areas.

Section 16.16 prohibits infiltration where soil infiltration rates exceed 8.3 inches per hour. However, the permit does allow the soils to be modified, such as with organic material, to reduce the infiltration rate to less than 8.3 inches per hour. Therefore, the prohibition on excessively high infiltration rates will not be considered as prohibitive of infiltration practices in this analysis.

Table 2.1 Data Sources used in the PIR

Parameter	*Source*
Saturated Hydraulic Conductivity	(USDA NRCS, 2017)
Depth to Groundwater	(USDA NRCS, 2017)
Relative Elevation	(Minnesota Department of Natural Resources, n.d.)
Topographic Slope	(Minnesota Department of Natural Resources, n.d.)
Wetlands	(Minnesota Department of Natural Resources, 2017)
Contaminated Soils	(Minnesota Pollution Control Agency, 2017b)
Depth to Bedrock	(Minnesota Geologic Survey, 2016)
Hydrologic Soil Group	(USDA NRCS, 2017)
Drinking Water Emergency Response Areas	(Minnesota Department of Health - Environmental Health Division - Source Water Protection Unit, 2014)
Drinking Water Supply Management Areas	(Minnesota Department of Health, 2017)
Karst Features	(Minnesota Department of Natural Resources, 2016)

2.2 FUZZY LOGIC MODEL

A fuzzy logic model implemented in a geographic information system (GIS) is proposed, the output of which is a raster that can be displayed on a map. Select elements from the MAR study proposed by Ghayoumian et al., (2007) are utilized. The relative elevation proposed by Miller (2014) is incorporated into the proposed fuzzy logic model to account for the ability to direct stormwater to an area by gravity drainage. Environmentally sensitive layers applicable to the region of interest can be superimposed on the model, identifying locations where caution in siting infiltration practices is prudent.

In contrast to classical logic where a parameter is classified as either false or true, fuzzy logic allows for a parameter to be considered partially true. Infiltration-based SCMs have a range of potential performance with a gradual transition from excellent to poor. The parameters contributing to the overall performance exhibit a similar gradual transition from excellent to poor. A fuzzy logic model was thus selected to aggregate the variables into a composite rating.

Four variables were identified as important to the success of surface infiltration SCMs. These four variables were adapted from Ghayoumian et al., (2007) and Miller (2014). The K_{sat} of the soil within 2-meters of the surface is used to describe the limiting rate that stormwater can infiltrate into the subsurface. The depth to groundwater describes the likelihood of groundwater-surface water interactions occurring as a result of the infiltration-based SCM. The topographic slope relates to the constructability and safety of an infiltration-based SCM, as moderately steep slopes require larger footprints than minimal slopes to construct flat infiltration-based SCMs and infiltrating additional water near steep slopes may contribute to slope stability issues. The relative elevation describes the position on the hillslope and the potential to direct surface runoff to an area under gravity flow conditions. The PIR is defined by Equation 2.1.

Equation 2.1

$$PIR = WT_{Ksat} * WT_{dep2gw} * WT_{slope} * WT_{relel}$$

The variables WT_{Ksat}, WT_{dep2wt}, WT_{slope}, and WT_{relel} are weights associated with the K_{sat}, depth to water table, topographic slope, and relative elevation, respectively. The PIR equation outputs a number that is compiled into a category. Four categories are utilized to represent the relative likelihood of successfully implementing an infiltration SCM. The categories were established such that if a single input variable has a poor quality represented by a weight of 0.01, the composite category would be designated as Poor. However, if all input variable weights are greater than 0.01, the area will be rated as Moderate, Good, or Excellent.

The Soil Data Viewer tool in ArcMap is used to extract the K_{sat} and depth to water table from the SSURGO dataset (USDA NRCS, 2017). Both variables are aggregated for the dominant component of the soil map unit. K_{sat} is aggregated as a weighted average over all soil layers. The weighted average was selected because it is available within the Soil Data Viewer tool, although the analysis may be improved by using the geometric mean, if available. The depth to water table is conservatively selected as the lowest value (e.g., highest elevation) over the calendar year. The vector layer is converted to a raster with a 10-meter resolution, which approximates the level of detail provided in the vector polygons.

The workflow utilizes a digital elevation model (DEM) with a 10-foot (3-meter) horizontal resolution to capture the local variability of terrain features. Alternative resolutions likely could be utilized but have not been evaluated as part of the present study. In this study a LiDAR derived DEM was retrieved from MnTOPO (Minnesota Department of Natural Resources, n.d.). The slope is calculated using the ArcMap D8 slope routine. The relative elevation proposed by Miller (2014) was calculated from the DEM and normalized by the difference between the minimum and maximum elevations in the 443-foot (135 meter) local neighborhood. The 443-foot (135 meter) local neighborhood was identified by Miller (2014) as the optimal scale to analyze relative elevation by comparing field observations to GIS calculated values. Normalizing the relative elevation converts the relative elevation to a dimensionless number in the range of -1 (lowest elevation) to 1 (highest elevation), representing the position on the hillslope. Both the slope and relative elevation are resampled using a bilinear interpolation to a 10-meter resolution and snapped to the soil raster. A flow chart describing how these variables are aggregated is provided in Figure 2.1.

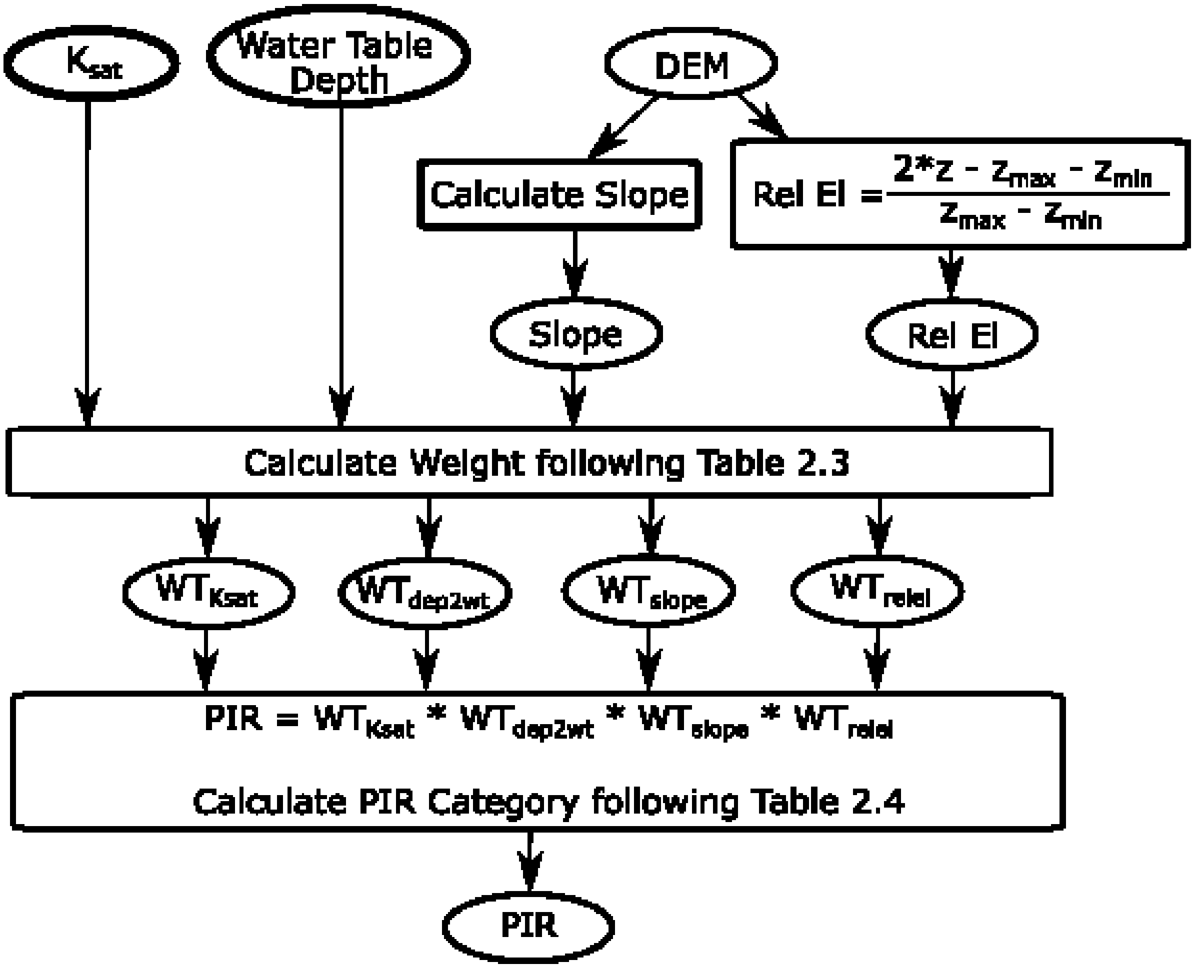

Figure 2.1 Overview of the key components required to calculate the PIR. Ovals represent data and rectangles represent calculations.

2.3 CALIBRATION AND VALIDATION

The proposed fuzzy logic model was calibrated and validated with a rain garden maintenance dataset (Anoka Rain Gardens) from the Anoka Conservation District (2019). Anoka County is part of the Minneapolis-Saint Paul metropolitan area in Minnesota. However, the workflow should be applicable in other regions where the required spatial data is available. The workflow that was developed can be implemented over a range of scales from the resolution of the output raster to county-wide scale.

Rain gardens are the only type of surface infiltration SCM that was included in the Anoka Rain Gardens dataset, consisting of 115 existing infiltrating rain gardens. Rain garden performance was assumed to be representative of other types of surface infiltration SCMs. Among these there were 9 rain gardens that did not have SSURGO data available and 2 rain gardens that had not been inspected since construction, resulting in 104 rain gardens with sufficient data for this analysis. The rain gardens were constructed between 2010 and 2018. Visual inspections occurred between 2016 and 2019, resulting in rain gardens being assigned a letter grade that represents the performance and maintenance needs of the rain garden. The five letter grades used by the Anoka Conservation District correspond with the four PIR categories as shown in Table 2.2. The most recent inspection letter grade was used for rain gardens that had multiple inspections. In 5 cases, the most recent inspection notes indicated a lower letter grade was given due to pretreatment maintenance issues rather than a lack of infiltration capacity. In these 5 cases the next most recent inspection rating was utilized. In an additional 4 cases, an underdrain was installed after initial construction. It was presumed the retrofitted underdrain indicated the rain garden had not been functioning adequately and these rain gardens were rated as Poor in the PIR category. The Anoka Rain Gardens were randomly separated into a calibration set containing two thirds of the data and a validation set containing one third of the data as shown in Figure 2.2. The number of rain gardens associated with each Anoka Letter Grade and PIR category are shown in Table 2.2.

Table 2.2 Anoka Conservation District Rain Garden Maintenance Inspection Grades, Criteria, and Associated PIR Category.

Anoka Letter Grade	Anoka Grading Criteria	PIR Category	Count in Calibration	Count in Validation
A	Excellent. All functions are working. No maintenance is required.	Excellent	18	15
B	Good. The primary functions are working. Some regular maintenance is required.	Good	39	12
C	Fair. Erosion impacts are likely or have already happened and/or other functions are not working; light maintenance is required.	Moderate	4	6
D & F	(D) Poor. Erosion impacts are likely or have already happened and/or other functions are not working; structural maintenance, retrofit, or re-design is necessary. (F) Failing. The rain garden is not providing any functions and/or the rain garden is not present.	Poor	9	1

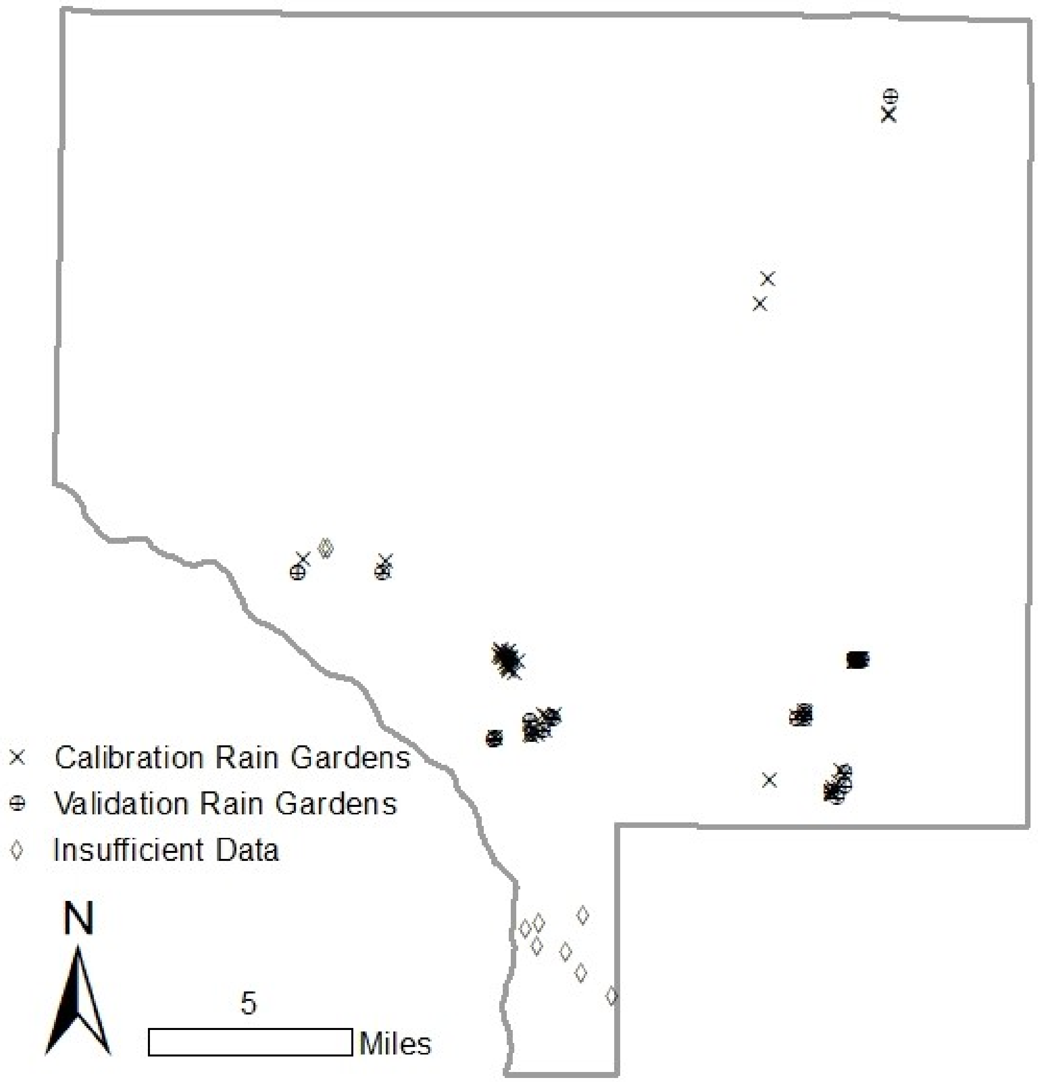

Figure 2.2 Rain gardens monitored by the Anoka Conservation District.

The calibration set of 70 rain gardens was used to modify the weights and categories associated with the PIR fuzzy logic model. The goal of the calibration was to provide a rating where the constructed surface infiltration-based SCM was likely to perform as well or better than predicted by the PIR. Table 2.3 shows the calibrated input variable categories and associated calibrated weight. The calibrated PIR categories are shown in Table 2.4.

Table 2.3 PIR Input Variable Weights

Variable	Weight
$K_{sat} \leq 0.2$ in/hr ($K_{sat} \leq 5$ mm/hr)	0.01
0.2 in/hr $< K_{sat} \leq 0.6$ in/hr (5 mm/hr $< K_{sat} \leq 15$ mm/hr)	0.35
0.6 in/hr $< K_{sat} \leq 1$ in/hr (15 mm/hr $< K_{sat} \leq 25$ mm/hr)	0.45
1 in/hr $< K_{sat} \leq 1.8$ in/hr (25 mm/hr $< K_{sat} \leq 45$ mm/hr)	0.75
1.8 in/hr $< K_{sat}$ (45 mm/hr $< K_{sat}$)	0.95
dep2wt < 39.4 in (dep2wt < 100 cm)	0.01
39.4 in ≤ dep2wt < 78.7 in (100 cm ≤ dep2wt < 200 cm)	0.3
78.7 in ≤ dep2wt (200 cm ≤ dep2wt)	0.5
10% < slope	0.01
4% < slope ≤ 10%	0.3
2% < slope ≤ 4%	0.5
Slope ≤ 2%	0.7
0.75 < Rel El	0.01
0 < Rel El ≤ 0.75	0.3
-0.5 < Rel El ≤ 0	0.5
-1 < Rel El ≤ -0.5	0.7

Table 2.4 PIR Composite Rating Categories

PIR Category	PIR Value
Poor	PIR ≤ 0.009
Moderate	0.009 < PIR ≤ 0.05
Good	0.05 < PIR ≤ 0.1
Excellent	0.1 < PIR

The calibrated PIR for Anoka County is shown in Figure 2.3. An error matrix is a common tool for assessing the accuracy of a classification model (Congalton, Oderwald, & Mead, 1983). An error matrix of the calibration dataset is shown in Table 2.5, where the columns of the error matrix represent the true category, in this case the Anoka Rain Gardens inspection category. The rows of the error matrix represent the model predicted category, in this case the PIR predicted category. The values in the error matrix are a count of the number of rain gardens with the given characteristics. The major diagonal from the upper left to lower right therefore represents the instances where the model predicted category matches the true category. The accuracy of the model is defined by the sum of the values along the major diagonal divided by the total number of data points. Cells that are below the major diagonal represent rain gardens where the model conservatively predicted a level of performance less than what was observed. Cells that are above the major diagonal represent rain gardens where the model non-conservatively predicted a level of performance better than what was observed.

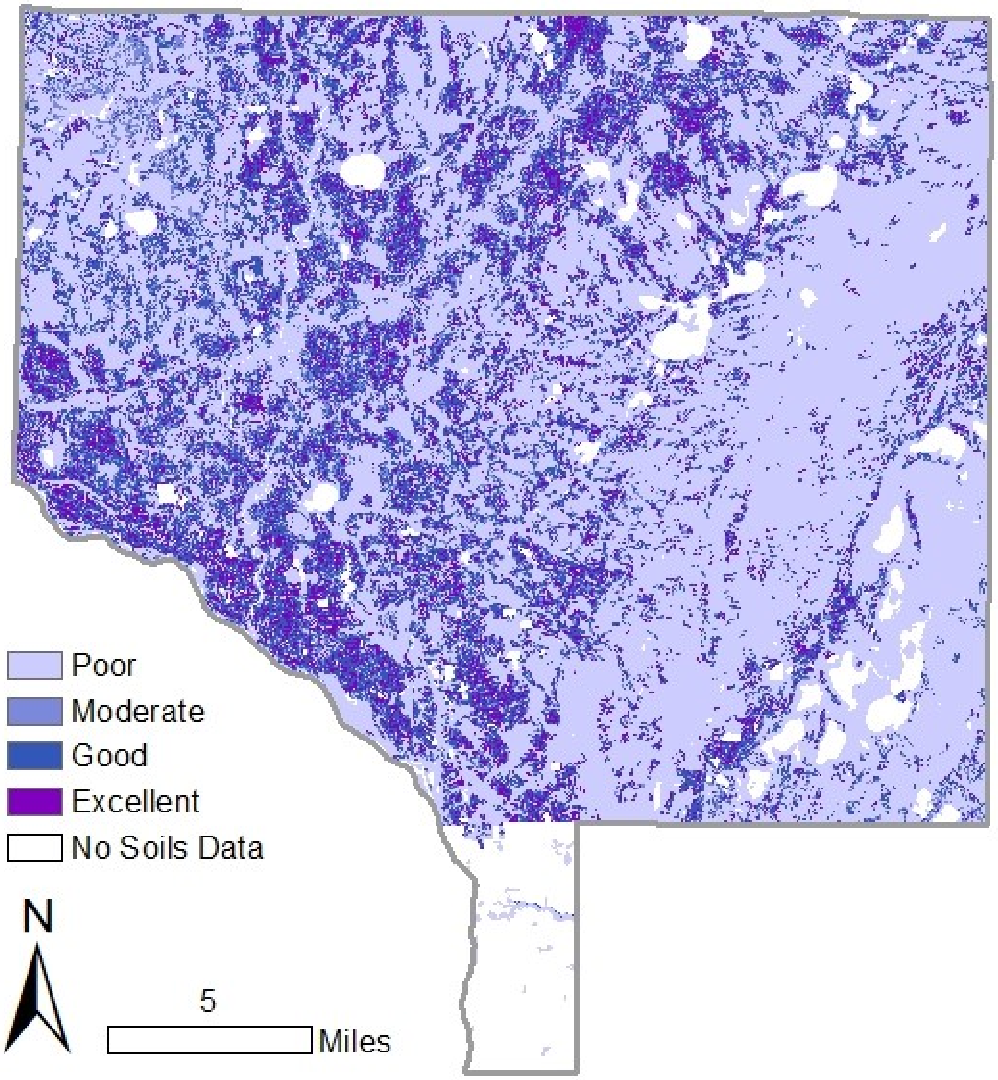

Figure 2.3 Preliminary Infiltration Rating (PIR) for Anoka County, MN

The PIR accurately predicted the Anoka Rain Garden category in 30% of instances in the calibration rain gardens. The PIR provided a conservative prediction for 51% of the rain gardens, and a non-conservative prediction for 19% of the rain gardens. The PIR therefore resulted in a correct or conservative category prediction for 81% of the calibration rain gardens, indicated by the counts in bold font in Table 2.5. Of the four rain gardens that were specified as Poor in the Anoka Inspection Categories because underdrains were installed following initial construction, the PIR Category was accurately predicted as Poor in two instances, and incorrectly predicted as good and excellent, respectively, in the other two instances.

Table 2.5 Error matrix of calibration rain gardens. Accurate or conservative results are shown in bold.

	Anoka Inspection Category			
PIR Category	Excellent	Good	Moderate	Poor
Excellent	**1**	5	0	2
Good	**12**	**16**	3	3
Moderate	**4**	**9**	**0**	0
Poor	**1**	**9**	**1**	**4**

When the PIR incorrectly assigned a Poor category to a rain garden rated as Excellent, Good, or Moderate by the inspections, the depth to water table variable was the most common variable that resulted in a PIR rating of Poor. When the PIR incorrectly assigned a category of Excellent or Good to a rain garden rated as Poor by the inspections, the inspection notes typically mentioned difficulty establishing and maintaining vegetative cover or post-construction structural changes, such as an added underdrain or reduced ponding depth which are indicative of poor infiltration.

A validation set of 34 rain gardens was used to verify the performance of the fuzzy logic model. The error matrix of the PIR for the validation Anoka Rain Gardens is shown in Table 2.6. The validation dataset has an accuracy of 21%. The PIR produced a conservative prediction for 65% of the rain gardens, and a non-conservative prediction for 15% of the rain gardens. A correct or conservative prediction is desirable, where the rain garden performs at least as well as predicted by the PIR. The PIR produced a correct or conservative prediction 85% of the time as indicated by the bold counts in Table 2.6, which is close to the calibration value of 81%.

Table 2.6 Error matrix of validation rain gardens. Accurate or conservative results are shown in bold.

	Anoka Inspection Category			
PIR Category	Excellent	Good	Moderate	Poor
Excellent	**3**	2	0	0
Good	**6**	**3**	2	1
Moderate	**2**	**2**	**1**	0
Poor	**4**	**5**	**3**	**0**

2.4 PIR LIMITATIONS

The following limitations to the use of the PIR technique should be noted:

1. The Anoka Conservation District maintenance inspection grade is based on a qualitative visual inspection of each rain garden. The criteria for the qualitative visual inspection are provided in Table 2.2, and comments were provided by the inspector to support the rating. Visual inspections are capable of determining the level of infiltration performance by observing factors such as standing water, hydrophytic vegetation, vegetative health, sedimentation, and surface crusting. The qualitative inspection ratings should be considered a general statement of the apparent rain garden performance on the day of the inspection.
2. Three of the four variables input to the PIR, the depth to water table, relative elevation, and topographic slope, were calibrated using the Anoka Rain Garden data set. The K_{sat} variable was not calibrated because all 104 rain gardens were located in areas where the K_{sat} in the SSURGO data set exceeded 1.8 in/hr (45 mm/hr). The K_{sat} weights shown in Table 2.3 were adapted from Ghayoumian et al., (2007) with minor modifications. An additional category was added to include soils with moderate infiltration potential in the range of 0.2 in/hr (5 mm/hr) to 0.6 in/hr (15 mm/hr), and the weights were adjusted to account for the additional category.
3. The output raster is at 33-foot (10-meter) resolution. Infiltration-based SCMs can vary from less than 100 square feet to 1000s of square feet. The raster is not meant to be a definitive statement on the infiltration capability of an exact point. Rather it should be considered a general statement of the capability of an area to support future infiltration SCMs. The fuzzy logic model was established such that the underlying data sets contributing to the rating of a location could be evaluated and the rating confirmed. Therefore, similar results likely could be obtained

by critically evaluating each of the input variables manually. The proposed fuzzy logic model allows large areas to be evaluated rapidly and consistently.

4. The PIR is most suitable in urbanizing areas where SSURGO data is available, and when the existing and proposed topography are relatively similar. Ultra-urban areas with disturbed soils are not well represented by the SSURGO data set. Extensive earthwork during the proposed construction would limit the relevancy of all input variables. The PIR has limited applicability to subsurface infiltration systems. The PIR is intended as a preliminary screening tool and is not a replacement for thorough field investigation and proper design. Engineered media selection, pre-treatment performance, and maintenance protocols are not described in this preliminary screening tool but influence the ultimate infiltration performance. These factors should be considered in the design process and life cycle of the infiltration SCM.
5. Finally, the PIR is based on data sets for which each have an associated uncertainty. Notably the K_{sat} and depth to water table are both highly variable in space and time. An understanding of the uncertainty associated with the inputs is critical to an appropriate understanding of the PIR uncertainty and should be considered in any decision-making process.

2.5 PIR APPLICATION

Land development that increases impervious surface area is often required to mitigate the associated hydrologic impacts using an infiltration SCM. Land development includes transportation, residential, and commercial construction projects in both the private and public sectors, as well as other land altering projects. A planning phase tool such as the PIR that identifies the likelihood of a given site being suitable for an infiltration-based SCM can guide early land-development planning, enhance communication between technical and non-technical stakeholders, and reduce the number of sites that require detailed field investigation.

Examples implementing the PIR and incorporating overlays for environmentally sensitive areas for a transportation corridor and a municipality are shown in Figure 2.4. The displayed environmentally sensitive areas are based on the MPCA Construction Stormwater General Permit prohibitions (Minnesota Pollution Control Agency, 2018). There may be other types of restrictions or areas where infiltration is not desirable, such as critical habitat or culturally sensitive areas, that can be included as an overlay if the GIS data is available. Both examples are located within the Minneapolis-Saint Paul metropolitan area as shown in Figure 2.4a. Information relating to the presence of wetlands, shallow bedrock, karst features, and drinking water supply management areas are all included in the environmentally sensitive areas layer overlaid on the PIR. Figure 2.4b shows a corridor of I-35E that may increase impervious surface requiring consideration of infiltration-based SCMs. The northern portion of the corridor is observed to include environmentally sensitive areas where infiltration is likely not appropriate. The southern portion of the corridor includes sites with a range of potential infiltration performance. These sites can be evaluated in the context of other project considerations, allowing locations with a high potential for success to be identified early in the planning process. Figure 2.4c shows the City of Woodbury located in Washington County, Minnesota. The eastern portions of the city are environmentally sensitive areas, north western portions of the city have a lower potential to support surface infiltration-based SCMs, and south-central portions have a higher potential to support surface infiltration-based SCMs. When utilized as a planning tool, additional project specific data can be included. This data could include information from CAD such as alignments, information related to property lines and right-of-way, or other relevant spatial data. The examples in Figure 2.4 are intended to show broad variation over large areas. However, the figures could be produced at the scale of plan sheets for critical evaluation. The 10-meter pixel provides variation over relatively small spatial scales such as the right-of-way width. The PIR resolution is sufficiently refined to be influenced by roadway embankments but is not sufficiently refined to capture small topographic variations such as curbs or roadway crowns. In both transportation and municipal contexts, the PIR in combination with environmental data provides a rapid screening of areas where infiltration is likely to be successful. The tool to create the PIR was built in the ArcMap environment, and Appendix A provides detailed steps that a GIS user can follow to create the PIR. A map such as shown in Figure 2.4 can be completed in approximately 2 to 4 hours.

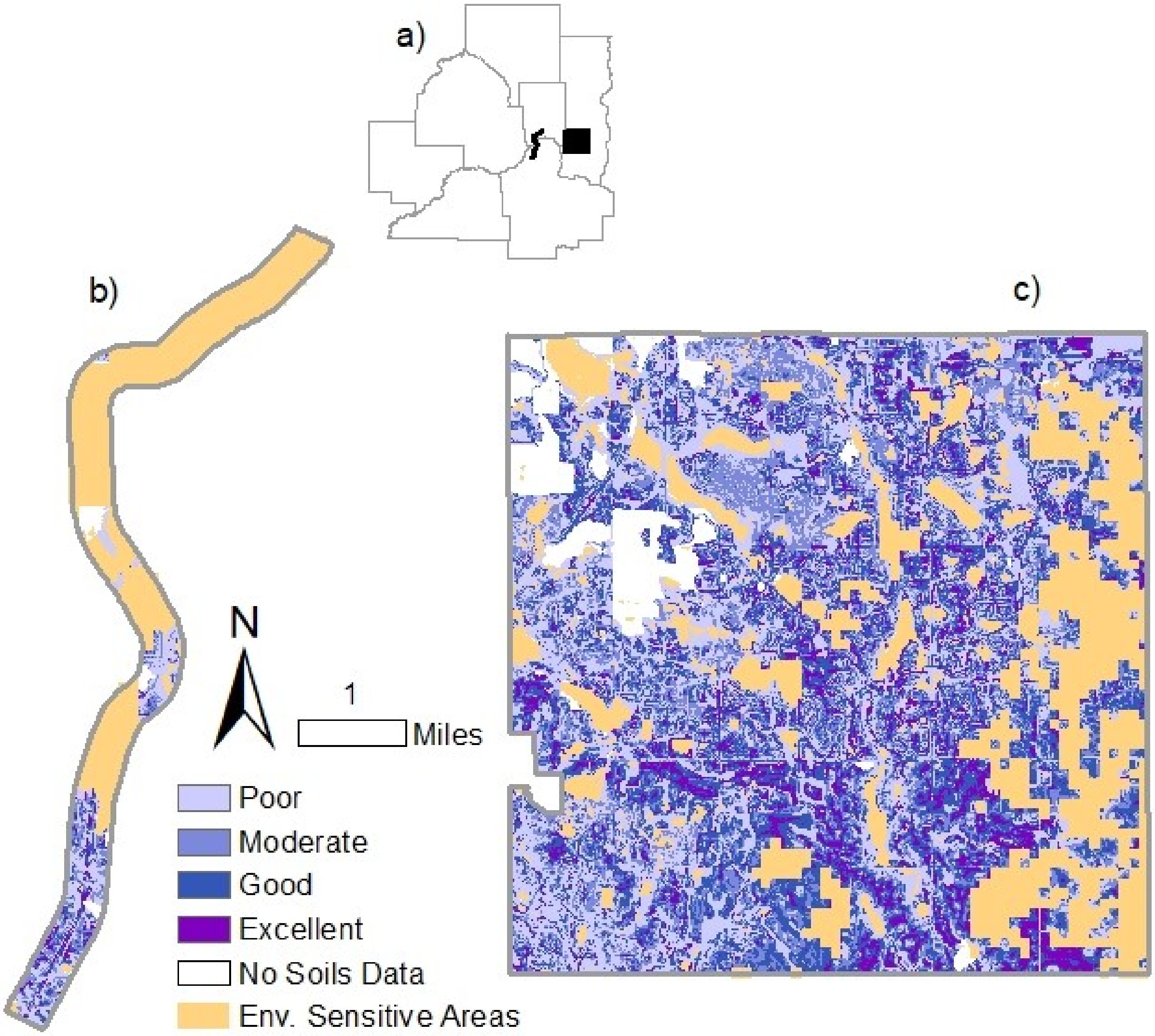

Figure 2.4 Examples implementing the Preliminary Infiltration Rating (PIR) with overlays of environmentally sensitive areas. a) Minneapolis-St. Paul metropolitan area with locations of examples. b) I-35E from 10th Street in St. Paul, MN to Lone Oak Road in Eagan, MN. c) the City of Woodbury, MN.

The PIR provides an effective method of identifying areas where surface infiltration SCMs are likely to be successful, prior to site-specific field investigations. The map of the PIR categories can be combined with other relevant spatial data, such as environmentally sensitive areas or property information, to identify the most suitable sites for surface infiltration SCMs. The PIR improves on simplistic desktop analyses, such as relying exclusively on hydrologic soil group, by incorporating additional relevant variables into a composite rating that is easy to interpret and requires nominal additional time. The PIR can serve as a communication tool between technical and non-technical stakeholders, as well as a guide to identifying locations for detailed site-specific investigation. A detailed procedure for implementing the PIR is included in Appendix A.

CHAPTER 3: IN-SITU INFILTRATION MEASUREMENTS

3.1 INFILTRATION MEASUREMENT METHODS

Saturated hydraulic conductivity (K_{sat}) is naturally a highly heterogeneous soil property. Variability of up to two orders of magnitude has been observed on the scale of less than 10 feet (Asleson et al., 2009; Gupta et al., 2006; Press, 2019). The natural heterogeneity introduces uncertainty in all infiltration measurement methods. Methods that incorporate larger soil volumes tend to provide a bulk average. Methods that incorporate smaller soil volumes tend to be simpler to complete, allowing a larger number of measurements to be completed to capture the heterogeneity. In addition to the natural heterogeneity, potential sources of measurement error in the field include disturbance of the soil when placing the infiltrometer, suspension and resettling of fines when applying water, influent chemical composition, and influent temperature.

The double ring infiltrometer (DRI) described by American Society for Testing and Materials (ASTM) (2018c) is an industry standard infiltration measurement method, utilizing a 12-inch (30-cm) inner ring, 24-inch (60-cm) outer ring, and a constant head for a 6-hour duration. The DRI assumes 1-dimensional flow within the inner ring. Lai & Ren (2007) suggested that a double ring infiltrometer with a larger diameter inner ring, exceeding 31 inches (80 cm), better represents the hydraulic conductivity of heterogenous soils relative to smaller diameter inner rings. The large double ring infiltrometers can be challenging, and researchers have investigated the compromise of ring size and ease of use. Gregory et al., (2005) found a double ring infiltrometer (DRI) with a 15-cm inner ring, 30-cm outer ring, and constant head condition was suitable for measuring infiltration rates in sandy soils. Compacted soils often require the DRI to be jacked into the ground, which is difficult or prohibited at infiltration SCMs where driving on the surface is to be avoided. The 1-dimensional flow assumption used in the DRI is also likely to introduce a non-conservative bias error. Finally, the DRI is time-consuming and water intensive, which can result in fewer DRI tests being completed at each site.

The Modified Philip-Dunne (MPD) infiltrometer described in American Society for Testing and Materials (ASTM) (2018b) is a falling head device that uses a single ring with a 4 inch (10 cm) diameter. Relative to the DRI, the MPD infiltrometer is smaller, easier to insert into the soil, and requires less water. The MPD assumes a 3-dimensional saturation zone in the shape of a capped sphere forms and expands as the water level in the cylinder drops. The MPD calculates the K_{sat} and soil suction head (Ψ) as an optimization of the head versus time curve using the Green-Ampt assumptions. Previous studies have indicated the MPD and DRI perform similarly (Garza et al., 2017; Nestingen et al., 2018), although the smaller surface area of the infiltration test may result in greater variation of the results.

The Turf-Tec IN2-W (TT) by Turf-Tec international (Turf-Tec International, n.d.-a) is a small double ring infiltrometer. The inner ring is 2-3/8 inch (6.03 cm) and the outer ring is 4.25 inches (10.79 cm). The device is simple to use and the method to calculate results is intuitive. The Turf-Tec can be easily inserted, and the water requirement is minimal. Multiple replicates of the falling head test are recommended until the infiltration rate is observed to approximately stabilize. The TT is commonly used in turf-management, and while a user's manual is provided an ASTM standard does not exist. Similar to the DRI, the 1-dimensional flow assumption of the TT likely introduces a non-conservative bias error. Since the diameter of the TT is smaller than the ASTM standard DRI, this error is likely larger.

The soil texture (ST), also referred to as soil classification, can be determined from a pit or boring (ASTM International, 2018a). Estimating the infiltration rate from the soil classification can be completed using the Minnesota Stormwater Manual and available literature (Minnesota Pollution Control Agency, 2017a; Rawls et al., 1998). An ASTM standard is not available for directly estimating infiltration rate from soil texture, however. Soil texture is important for understanding the soil profile including vertical variations in soil texture, seasonal groundwater fluctuations, and the presence of confining layers. The variability in infiltration rate predicted by soil texture likely does not fully represent the heterogeneity that exists because it does not consider soil compaction or the presence of macropores.

This chapter will focus on estimating infiltration capacity utilizing the double ring infiltrometer (DRI), Modified Philip-Dunne Infiltrometer (MPD), the Turf-Tec Infiltrometer (TT), and soil texture (ST). Table 3.1 provides a comparison of these different methods. The MPD, DRI, and TT each provide information about site specific soils, while ST provides information typical of the soil class, such as a K_{sat} value, based on the literature. The DRI is a steady state test that involves the largest soil volume, the MPD is a falling head test that involves the next largest soil volume, and the TT is a falling head test that involves the smallest soil volume. The relative water usage of each falling head device is proportional to the tested soil volume. The MPD and TT can often be implemented in less than 1 hour, while the ASTM standard for the DRI requires a 6-hour test duration. None of the methods directly measure K_{sat}. The MPD implements an optimization procedure that uses the observed time variable head, change in volumetric soil water content, and device geometry to estimate the field saturated hydraulic conductivity. The DRI and TT measure an infiltration rate that is often assumed to approach K_{sat} as the infiltration rate approaches steady state. This assumption is based on the idea that the hydraulic gradient approaches unity in the flow beneath the device, which can be accurate if applied properly. An assessment of the soil profile characteristics is important for the DRI, MPD, and TT as confining layers and seasonally high groundwater are difficult to identify using infiltration tests alone. The natural heterogeneity of soils would suggest that multiple measurements are required regardless of the selected method. The method to measure K_{sat} or infiltration rate for a given site should be based on the required level of accuracy, the availability of water, the available time to complete testing, and the available budget. Table 3.1 compares the methods that were evaluated in detail in the field. Discussion of additional methods identified in the literature and on the selection of a method is provided in Chapter 5.

Table 3.1 Comparison of methods to estimate soil properties under field conditions

	Modified Philip-Dunne Infiltrometer[a]	Double Ring Infiltrometer[b]	Turf-Tec Infiltrometer[c]	Soil Classification[d]
Property Measured	K_{sat}[e]	Infiltration Rate	Infiltration Rate	Soil Texture
Test Surface Area	12.2 in^{2} (79 cm^{2})	110 in^{2} (707 cm^{2})	4.4 in^{2} (29 cm^{2})	1.8 in^{2}[f] (11 cm^{2})
Number of Rings	single ring	double ring	double ring	n/a
Constant/Falling Head	Falling Head	Constant Head	Falling Head	n/a
Typical Test Duration	30 – 60 minutes	2 hours[g] – 6 hours	15 minutes per test, repeated 2-3 times	Varies
Typical Required Water Volume	0.66 gallons (2.5 liters)	1.9 to 164 gallons (7.3 to 620 liters)	0.33 gallons (1.25 liters)	n/a
Assumed Flow Dimensionality	3-D	1-D	1-D	n/a
Recommended Operating Range	0.1 – 591 in/hr (0.25 – 1500 cm/hr)	0.01 – 14.2 in/hr (0.036 – 36 cm/hr)	0.125 – 42 in/hr (0.32 - 107 cm/hr)	n/a

a) (ASTM International, 2018b)
b) (ASTM International, 2018c)
c) (Turf-Tec International, n.d.-b)
d) (ASTM International, 2018a)
e) The MPD procedure directly measures a head versus time curve, then calculates a field saturated hydraulic conductivity (K_f) by optimizing K_f and soil suction head (ψ)
f) (ASTM International, 2011)
g) Wisconsin Department of Natural Resources (2017) allows for the test duration to be reduced to 2-hours

3.2 NUMBER OF INFILTRATION MEASUREMENTS

It is important to define the required number of samples prior to beginning the measurement collection in the field. This allows for communication between office staff and field staff and an establishment of field procedures. However there is no consensus on the number of infiltration measurements required to characterize an area. Bouwer (1986) suggests a minimum of 5 infiltration measurements, then continuing to complete replicates until an acceptable margin of error is achieved. Ahmed, Gulliver, & Nieber (2015) recommend 20 MPD measurements be collected so the 95% confidence interval is between a factor of 1.8 and 2.2 of the geometric mean. Sandoval, Galobardes, Teixeira, & Toralles (2017) recommend 7 to 8 infiltration measurements are required for the error to be within 10% of the mean for determining infiltration rates on pervious concrete. Press (2019) measured the infiltration capacity of rain gardens using both point measurements and monitoring the basin-wide recession rate. Press (2019) normalized the standard deviation of the infiltration point measurements by the basin-wide recession rate, and suggested that 5 to 6 infiltration measurements are required so this ratio will be less than 50%. Minnesota Pollution Control Agency (2018) allows for a single measurement to characterize the infiltration rate of a proposed infiltration SCM. As there is not an agreed upon minimum number of measurements to characterize an area, or an agreed upon procedure for determining the minimum number, a statistical procedure will be considered herein.

One typical statistical method calculates the minimum sample size as a function of the required level of confidence, the standard deviation of the distribution, and the acceptable margin of error. The level of confidence refers to the probability that the true parameter is included in a given data set. The acceptable margin of error defines the tolerance for deviation between the sample parameter and the true parameter. The formula to calculate sample size (n) for a single sample, with a continuous outcome, and a normal distribution is shown in Equation 3.1. The variable z is the z-score associated with the level of confidence, s_x is the sample arithmetic standard deviation of the distribution, and E is the acceptable margin of error.

Equation 3.1

$$n = \left(\frac{z * s_x}{E}\right)^2$$

However, the spatial distribution of K_{sat} and infiltration rate has been found to follow a log-normal distribution, violating one of the assumptions of the sample size calculation. A geometric mean is appropriate to describe the central tendency of a log-normal distribution as given in Equation 3.2.

Equation 3.2

$$\boldsymbol{\overline{x}_{geo} = \sqrt[n]{x_1 * x_2 * x_3 * \cdots * x_n}}$$

Correspondingly the geometric standard deviation (GSD) is a more appropriate measure of spread for a log-normal distribution that the arithmetic standard deviation. The GSD is multiplicative whereas the arithmetic standard deviation is additive. For example, one geometric standard deviation above or below the geometric mean would be calculated as the geometric mean multiplied by the GSD and the geometric mean divided by the GSD, respectively. The equation to calculate the GSD of a sample (Kirkwood, 1979) is shown in Equation 3.3.

Equation 3.3

$$GSD(x) = exp\left[\sqrt{\frac{\sum_{i=1}^{n}\left(ln\, x_i - ln\, \bar{x}_{geo}\right)^2}{n-1}}\right] = exp[standard\ deviation(ln\, x_i)]$$

GSD(x) is the geometric standard deviation of the variable x, x_i is the individual values, $\bar{x}_{geo}$ is the sample geometric mean, and n is the count of x_i. By definition, a log-normal variable is normally distributed in log space. Therefore, we can use Equation 3.1 to calculate sample size if the standard deviation and margin of error are both in log space and if we substitute the GSD for the arithmetic standard deviation. Since the error is applied in log space, the margin of error (E) is multiplicative, and the square of the margin of error is the ratio of the upper bound to lower bound of the expected range. An equivalent formula for Equation 3.1 written for a log-normal distribution is shown in Equation 3.4.

Equation 3.4

$$n = \left(\frac{z * log(GSD)}{log(E)}\right)^2$$

The z-score corresponds to the desired level of confidence. The margin of error, E, represents the acceptable tolerance. Therefore, these two values need to be selected based on the application and required accuracy.

The GSD of K_{sat} varies with local heterogeneities and can be calculated from the measurements at each site. However, we will estimate a representative GSD value from literature for use in sample size calculations prior to collecting site-specific field data. Rawls et al., (1998) provides a geometric mean, 25th percentile, and 75th percentile K_{sat} value for a range of soil types in both a compacted and uncompacted condition. The geometric mean of K_{sat} values in the compacted condition are the basis for the MPCA stormwater manual guidance, and we believe that these values would represent the accuracy of the soil classification technique. If we assume that K_{sat} for each soil type is log-normally distributed, then the GSD can be calculated using Equation 3.5. If the GSD calculated from the 25th and 75th percentile of a given soil type are approximately equal, then the log-normal assumption is likely valid.

Equation 3.5

$$GSD = \left(\frac{Q_1}{\bar{x}_{geo}}\right)^{-1.5} = \left(\frac{Q_3}{\bar{x}_{geo}}\right)^{1.5}$$

Q_1 and Q_3 in Equation 3.5 refers to the 25th and 75th percentile, which are used with the negative and positive exponent, respectively. The plot of GSD based upon the 25th percentile and 75th percentile shown in Figure 3.1 and calculated from Equation 3.5 appears to have several values that do not meet the equality criteria (e.g. lie close to the 1:1 line). To determine if outliers are present in the data set, the median of all absolute deviations (MAD) was utilized (Rousseeuw, 1990). Five soil texture and compaction condition combinations were determined to be outliers. The outliers were typically low conductivity soils. As these are not representative of soils in most infiltration SCMs, they were excluded. Figure 3.1 shows the GSD of each soil texture calculated using the 25th and 75th percentile, respectively, and plotted against a 1:1 line. The geometric mean of the GSD data set with outliers removed was calculated to be 3.27. This is proposed to be a representative GSD for sample size calculations.

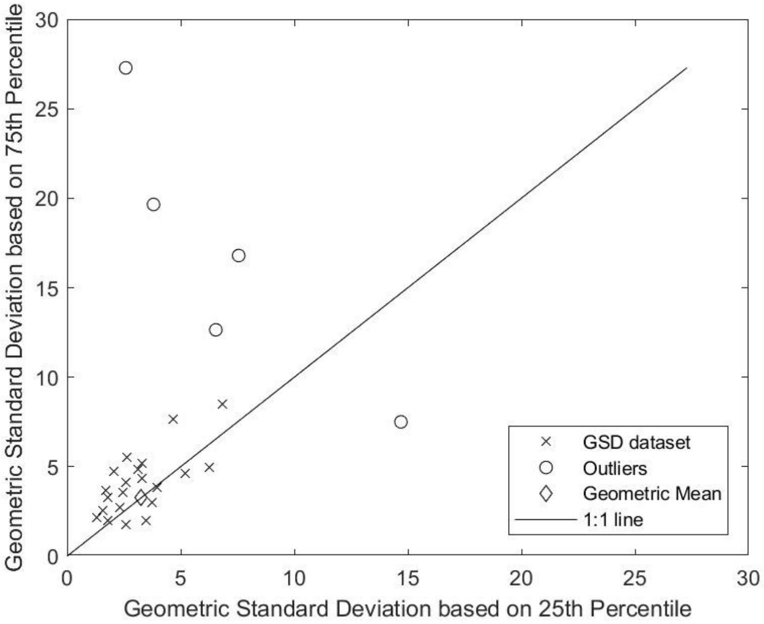

Figure 3.1 Geometric standard deviation of saturated hydraulic conductivity calculated using the 25th and 75th percentile of each soil texture described by Rawls et al., (1998). The geometric mean of the GSD was calculated while excluding outliers.

Table 3.2 shows the required sample size for 5 different allowable errors at 4 different levels of confidence using a GSD of 3.27, which is believed to be a reasonable measure of the spread of K_{sat} values. The range of allowable error shown in the header row is equal to the square of the allowable error. For example, the farthest right column would suggest that the sample geometric mean is within a factor of 10, or an order of magnitude, of the true geometric mean 95% of the time if 5 samples are completed.

Table 3.2 Required sample size for different acceptable error margins and levels of confidence, with a geometric standard deviation of 3.27

Range of Allowable Error from Geometric Mean (E^2)	1.2	2	3	5	10
Allowable Error (E)	1.095	1.414	1.732	2.236	3.162
Sample size with 67% confidence (n, z=0.97)	159	11	5	3	1
Sample size with 80% confidence (n, z=1.282)	278	20	8	4	2
Sample size with 90% confidence (n, z=1.645)	457	32	13	6	3
Sample size with 95% confidence (n, z=1.96)	648	45	18	9	5

The minimum size of the test area relative to the size of the SCM has not been well defined and the GSD depends more strongly on the soil than on the type of device utilized. The number of large-scale infiltration measurements, such as full-scale recession rates, may not be well represented by Equation 3.4 and Table 3.2. If there is a known change in the soil such as the texture, compaction condition, or surface cover, the areas should be sampled independently.

3.3 INFILTRATION MEASUREMENT RESULTS

Infiltration measurements were completed in 3 swales in the Twin Cities metropolitan area. Measurements of K_{sat} and infiltration rate were completed at the I-94 Weigh Station near Lakeland, MN in the Fall of 2019. Measurements were completed along TH-8 between Center City, MN and Shafer, MN and along TH-212 near Chaska, MN in the Fall of 2020. The locations are shown in Figure 3.2. The sites were selected so the infiltration measurements could be used in collaboration with soils data collected by the MPCA and MnDOT that can be found in Appendix B.

Heterogeneity in K_{sat} and infiltration measurements occurs over relatively small spatial scales. Infiltration measurements were completed in vegetated swales with a typical spacing ranging from 2.5 feet (0.75 meters) in the lateral direction to 33 feet (10 meters) in the longitudinal direction of the swale. Measurements were completed longitudinally at the swale centerline. Cross sections of 4 to 6 measurements were completed periodically extending to the top of bank on each side of the swale. Differences exceeding an order of magnitude were observed at adjacent MPD measurements with no apparent differences observed in the soil surface or test implementation. This variability is likely due to local changes in soil structure such as macropores or level of compaction. Additional guidance on how to establish sample spacing is included in Chapter 5.

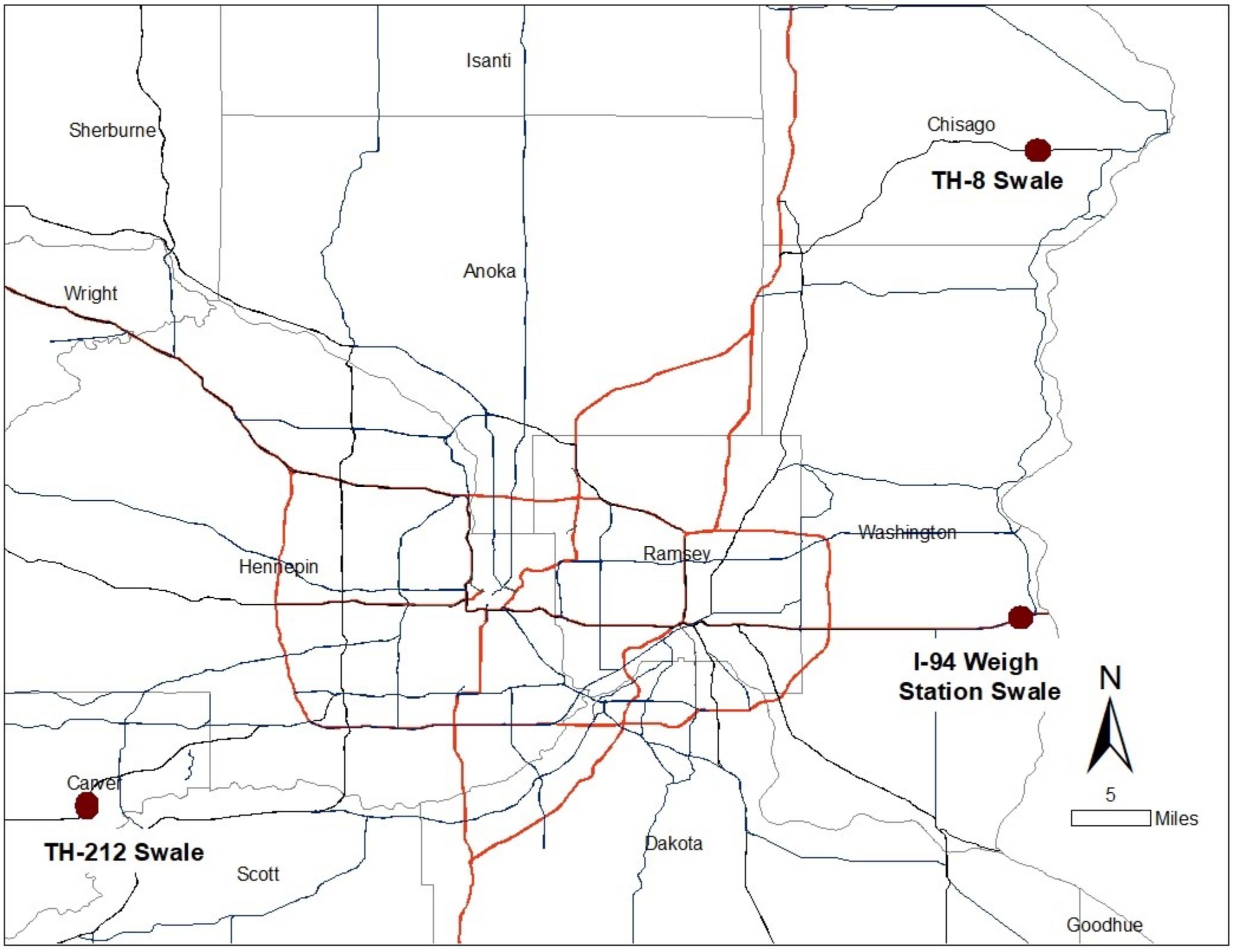

Figure 3.2 Swale locations along I-94 near Lakeland, TH-8 near Center City and Shafer, and TH-212 near Chaska

Summary statistics of each test measurement are shown in Table 3.3. The arithmetic standard deviation (SD) is observed to approach or exceed the arithmetic mean in multiple sites and methods. This would imply that a log-normal distribution may be more appropriate to represent the data as negative values of K_{sat} or infiltration rate are not possible. Table 3.3 also shows the geometric mean and geometric standard deviation (GSD), as these are more appropriate metrics for log-normal variables. An effective K_{sat}, calculated as a weighted average of the geometric mean and the arithmetic mean, is recommended by Weiss and Gulliver (2015) to aggregate spatially distributed K_{sat} measurements into a single representative value and is included in Table 3.3. Additional discussion of the effective K_{sat} is included in Chapter 5. Details regarding the individual MPD, DRI, and TT measurements completed at each swale are provided in Appendix C.

Soil profile descriptions at each swale were completed in June and July of 2017 by MnDOT staff (Minnesota Department of Transportation & Minnesota Pollution Control Agency, 2017). Summary statistics of the collected information is included in Table 3.3 and with additional data available in Appendix B. The infiltration rate corresponding to each layer in the soil profile was identified using the MPCA Stormwater Manual (Minnesota Pollution Control Agency, 2017a). The soil texture summary statistics in Table 3.3 are based on the geometric mean of the vertical soil profile at each soil boring. The soil was generally compacted or very compacted, although several borings note a loose layer below the surface layer.

Table 3.3 Summary statistics of infiltration rate measurements.

Swale Site	Measurement Method	Count	Arithmetic Mean [SD] (in/hr)	Geometric Mean [GSD] (in/hr)	Weiss & Gulliver (2015) effective K_{sat} (in/hr)	Range (in/hr)
I-94	MPD	62	9.4 [10.5]	3.9 [5.9]	5.7	0.01 – 44.9
I-94	DRI	10	1.8 [1.8]	0.9 [5.2]	1.2	0.02 – 5.1
I-94	TT	20	8.2 [12.9]	3.0 [5.1]	4.7	0.25 – 56.3
I-94	ST	14	0.5 [0.23]	0.5 [1.7]	0.5	0.14 – 0.8
TH-8	MPD	37	21.9 [28.8]	8.8 [5.3]	12.9	0.03 – 107.0
TH-8	DRI	6	1.9 [1.8]	1.0 [4.2]	1.3	0.09 – 4.9
TH-8	TT	19	4.2 [4.5]	2.2 [3.8]	2.9	0.13 - 18
TH-8	ST	13	0.2 [0.2]	0.2 [1.9]	0.2	0.09 – 0.6
TH-212	MPD	47	7.3 [14.6]	1.1 [11.9]	3.1	0.002 – 80.5
TH-212	DRI	7	5.6 [12.9]	0.6 [12.5]	2.2	0.01 – 34.9
TH-212	TT	20	10.8 [14.6]	4.0 [5.2]	6.2	0.16 – 58.8
TH-212	ST	14	0.2 [0.2]	0.1 [2.1]	0.1	0.06 – 0.8

Figure 3.3 shows relative frequency histograms of the measured values of K_{sat} or infiltration rate from each swale, plotted on a log-scale where each bar represents half an order of magnitude. The values measured using the MPD, DRI, and TT tend to have greater spread than those predicted based on soil texture. This is expected, as the soil texture based infiltration rates are based on a median value for each soil texture, assuming a compacted condition without vegetation, as reported in the literature (Rawls et al., 1998). Soil texture-based estimates of infiltration rate therefore miss both the high and low values and tend to underestimate the central tendency of the infiltration rate. For the Turf- Tec, measurements less than or equal to the detection limit were reported at the detection limit. All Turf-Tec replicates were

completed for a 15-minute duration or less. A longer duration (e.g. 1 hour) is required to differentiate low K_{sat} soils.

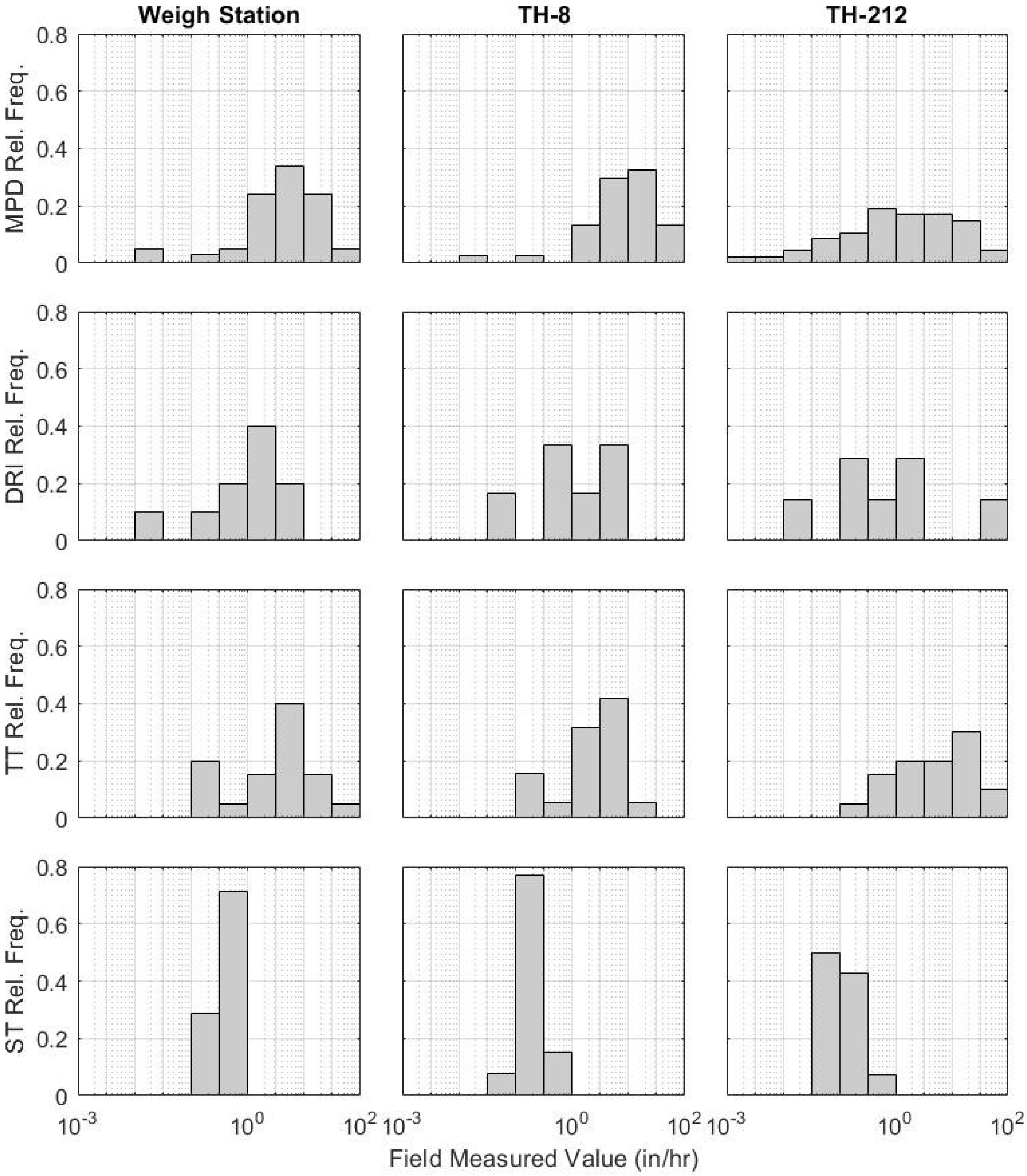

Figure 3.3 Relative frequency histograms of field measured K_{sat} (MPD) and infiltration rate (DRI, TT, and ST). Each column is a different swale. Each row is a different method. MPD is the Modified Philip-Dunne, DRI is the double ring infiltrometer, TT is the Turf-Tec, and ST is soil texture.

The difference in measured rates between methods may be partially due to the different soil volumes tested by each method, which is related to the volume of water used as illustrated in Table 3.1. It was not practical to complete soil profiles at each measurement location. Therefore, unidentified confining layers may have promoted lateral migration of water that would result in the infiltration rates measuring both the horizontal and vertical hydraulic conductivity. Consideration should thus be given to the appropriate quantity of water that relates to the application of the infiltration practices.

DRI and TT measurements were completed in close proximity to a MPD measurement, typically within 3 feet (1 meter), although the actual tested soil surface did vary. The methods also utilize different assumptions. The MPD assumes 3-dimensional flow with a capped spherical geometry, the DRI and TT both assume 1-dimensional flow, and the ST is based on literature values of the soil texture in a compacted condition.

If is of note that the ST does not capture the heterogeneity that is observed in all 3 of the other methods. The infiltration rate estimated by ST therefore has a narrow distribution and appears comparatively homogenous throughout each swale.

Infiltration SCMs are generally considered feasible in hydrologic soil groups A and B, somewhat feasible in hydrologic soil group C, and infeasible in hydrologic soil group D. Following the Minnesota Stormwater Manual (Minnesota Pollution Control Agency, 2017a) design infiltration rates for hydrologic soil groups A and B exceed 0.3 in/hr, design infiltration rates associated with hydrologic group C is 0.2 in/hr, and the infiltration rate for hydrologic soil group D is 0.06 in/hr. If soil texture alone was utilized for characterizing infiltration potential, only the I-94 Weigh Station is likely to have been considered feasible. However, the in-situ soil tests indicate that some level of infiltration performance may be possible at all 3 swales. In-situ testing of infiltration rate provides a more detailed description of the infiltration potential of an area than relying on soil texture alone.

3.4 FIELD MEASUREMENT LIMITATIONS

There is no independent reference standard with which to compare field measured values of K_{sat}. As such, it is not possible to determine the absolute error in an individual measurement. In addition, there are numerous sources of potential error in the field that are not readily quantified. Installing the devices always results in some level of disturbance to the soil. If there is a poor seal between the rings and the soil, short-circuiting is possible. Pouring the water into the devices can result in suspension of fines which can then settle in the pore space reducing the effective porosity.

When evaluating existing infiltration SCMs, the determination of a SCM having failed should be based on observed drawdown rates. Point infiltration measurements such as those discussed may give an indication of the drawdown rates, but due to soil heterogeneity the actual system performance may differ. Infiltration rates are known to vary over time including cyclic intra-annual variations. It is possible that a SCM with a poor infiltration rate can improve, such as with the establishment of vegetation.

MPD measurements were terminated when the cylinder emptied or after a minimum duration of 45 minutes. The MPD optimization procedure is most accurate when the cylinder drains completely. Therefore, there is some uncertainty in the low conductivity measurements when the test was terminated prior to the cylinder draining completely.

The DRI used had a 20 cm diameter inner ring, 40 cm diameter outer ring, and was installed with a 5 cm penetration depth. This is a smaller diameter and less penetration than the ASTM standard but does correspond to the recommendation of Gregory et al., (2005). The reduced penetration depth and smaller size was utilized to allow a consistent penetration depth to be achieved in compacted soils without requiring driving a truck with a jack in the swale.

The DRI measurements were completed for a range between 1 and 2 hours, less than the 6-hour minimum suggested in the ASTM standard but in correspondence with the recommended measurement period in Wisconsin (Wisconsin Department of Natural Resources, 2017). This could result in bias towards larger values of infiltration rate. The DRI produces an infiltration rate at interim times during testing. The DRI measurements were terminated when the variability in the measured infiltration rate appeared to reach a minimum within the measurement accuracy of the volume added over time.

The Turf-Tec replicates typically had a duration of 15 minutes. The duration was reduced to 3 or 5 minutes at high infiltration rate setups. The infiltration rate for the Turf-Tec infiltrometer was observed to stabilize as the number of replicates increases. A minimum of 2 replicates appears to be required for the infiltration rate to stabilize (e.g. infiltration rate variation between replicates reaches a minimum). For the measurements conducted during this study moist conditions were present in the field. In the case where dry conditions prevail, additional replicates may be required.

The lowest infiltration rate the Turf-Tec can measure in a 15-minute test is 0.125 in/hr (0.32 cm/hr). Any measurements at or below the detection limit were reported at the detection limit since a geometric mean and GSD cannot be calculated with a zero value. Therefore, the Turf-Tec geometric mean may be an overestimate, and the Turf-Tec GSD may be an underestimate. The Turf-Tec appeared to be sensitive to small soil variations such as macropores, likely due to the small diameter cylinders constituting the device.

CHAPTER 4: CALIBRATION OF SMALL, FALLING HEAD DOUBLE RING INFILTROMETER

4.1 TURF-TEC IN2-W

The Turf-Tec (TT) IN2-W infiltrometer, manufactured by Turf-Tec International, is a small diameter double ring infiltrometer that uses a falling head method to measure the infiltration rate rapidly with a minimal amount of water (Turf-Tec International, n.d.-a). The TT is easy to learn, use, and interpret. The TT is lightweight, easy to carry to the test location, and simple to insert and remove from the soil. The Turf-Tec does not require continuous monitoring during testing, which would allow an individual field technician to install and run numerous Turf-Tec setups simultaneously. Calculating the infiltration rate from the observed measurements is simple multiplication that could be completed by hand in the field. Each Turf-Tec replicate requires approximately 0.33 gallons (1.25 liters) of water, which an individual can transport to the site and carry to the TT setup without special equipment. The Turf-Tec rings are filled to the top and spilling water on the adjacent ground is acceptable, so the use of funnels or spouts is not necessary.

The Turf-Tec infiltrometer has primarily been used in the turf-management industry, with limited use in engineering applications. There are a relatively limited number of publications that describe the use of the TT for engineering applications. The TT operational guidance is based on the user’s manual since an ASTM standard does not exist. Pitt, Lantrip, Harrison, Henry, & Xue (1999) used the Turf-Tec infiltrometer to measure infiltration rates in predominantly sand and predominantly clay soils. The authors used 3 TT devices set up within 3 feet (1 meter) of each other to quantify spatial variability. Infiltration rates were noted every 5 minutes for a 2-hour test duration to allow the soils to approach saturation and a steady state infiltration rate. This is a deviation from the standard 15-minute test duration recommendation in the Turf-Tec manual, but within the suggested limits for low infiltration rate soils. Pitt & Lantrip (2000) noted that infiltration measurements using the TT were larger than expected but thought to be sufficient to indicate the relative effects of soil texture, compaction, and soil moisture on infiltration rates.

Sileshi, Pitt, Clark, & Christian (2012) utilized the TT, a large borehole infiltration test, and laboratory column test methods to evaluate infiltration potential in urban soils. Each method tested a different soil horizon and the laboratory column tests used different levels of compaction rather than undisturbed field samples. The authors suggested this created an overall indication of the infiltration potential of the soil. The authors suggest small scale infiltrometers, such as the TT, are useful if surface infiltration characteristics are of interest and borehole methods are useful when subsurface infiltration characteristics are of interest.

4.2 CALIBRATION

Tricker (1978) suggests that a single ring infiltrometer with a 2-inch (5 cm) diameter may have an error of a factor of 2.14. Bouwer (1986) estimated that a 2-inch (5 cm) single ring infiltrometer could overestimate the infiltration rate by a factor of 11. While the TT infiltrometer is a double ring device, the large variation in estimated error for small diameter single ring devices would suggest the TT is subject to systemic error and requires calibration.

The TT was utilized to measure infiltration rate in the swales discussed in Chapter 3. A total of 19 to 20 TT setups were completed at each swale, as described in Table 3.3. A minimum of 2 replicates were completed at each setup, although as many as 6 replicates were completed to observe the variation in infiltration rate. The infiltration rate measured in the final replicate was recorded as the infiltration rate for the setup.

As observed in Figure 3.3 and Table 3.3, the TT tended to overestimate an infiltration rate relative to the DRI. Using the Weiss & Gulliver effective K_{sat}, the TT overestimated the infiltration rate relative to the DRI by a factor of 3.9, 2.2, and 2.8 for the swales along I-94, TH-8, and TH-212, respectively.

Numerical simulations have been shown to be useful in evaluating infiltration measurements by isolating the known physical processes from the unknown soil heterogeneity (Ahmed et al., 2014; Sasidharan et al., 2020). Tecca et al., (2021a) investigated systemic bias of infiltration measurement methods including the TT and ASTM standard DRI using numerical simulations of infiltration into a homogeneous, isotropic soil. The systemic bias is defined as the ratio of the simulated infiltration rate to the known input K_{sat} of the soil. As shown in Table 4.1, the TT infiltration rate tended to overestimate the true K_{sat} by a factor from 2.2 to 5.3 in soil textures ranging from sand to silt loam. For the same soil textures, the DRI infiltration rate tended to overestimate the true K_{sat} by a factor of 1.2 to 1.5. As both methods are subject to systemic bias, the infiltration measurements completed in the swales are also biased and likely overestimate the K_{sat}. The numerically simulated ratio of the TT bias relative to the DRI bias ranges from 1.8 to 3.5, as shown in Table 4.1. As previously discussed in Chapter 3, the TT infiltration rate overestimated the DRI infiltration rate by a factor of 2.2 to 3.9. As the ratio of the TT to DRI infiltration rates are similar for the numerical simulations and swale field measurements, it is believed that this is a reasonable estimate of the TT overestimation relative to the DRI. The overestimation of the TT relative to the DRI is likely due to the 3-dimensional flow effects having a larger influence on the 1-dimensional infiltration rate for the smaller diameter TT than the larger diameter DRI.

Table 4.1 Systemic bias of the TT and DRI as found using numerical simulations (Tecca et al., 2021b)**. Results are reported for a relative soil moisture of 40%. Bias is defined as the ratio of the simulated infiltration rate to the known input K_{sat}.**

Soil Texture	TT bias	DRI bias	$\frac{TT\ bias}{DRI\ bias}$
Sand	2.2	1.2	1.8
Loamy Sand	2.4	1.2	2.0
Sandy Loam	3.0	1.2	2.5
Sandy Clay Loam	3.4	1.2	2.8
Silt Loam	5.3	1.5	3.5

Infiltration SCMs are typically sited in areas with coarse native soils. The engineered media of infiltration SCMs, and filtration SCMs, is typically a coarse sand mixture with a small fraction of organic material to promote plant growth. Table 4.1 would suggest that for coarse soils typical of infiltration SCMs, the TT tends to overestimate the true K_{sat} by a factor of 2.2 to 3. Correcting the TT field measurements by a factor of 3 may be a conservative method of estimating the infiltration rate. The bias in the TT increases substantially in finer soil textures. TT measurements in fine soils are also strongly influenced by antecedent soil moisture. Therefore, the TT should be considered qualitative in fine soils with use limited to comparative purposes.

4.3 FIELD USAGE

The TT has potential to be a useful tool in quantifying the infiltration rate of native soils and engineered media. The TT could potentially be used in any phase of an infiltration SCM life cycle including design, construction quality control, or maintenance inspections. As all soils are spatially heterogeneous, multiple field measurements are needed to characterize an area, and Table 3.2 may be useful in selecting the minimum number and understanding the associated uncertainty. The measurements should be spaced throughout the area that is being characterized.

A minimum of 2 replicates should be completed at each TT setup. The first replicate should be allowed to drain for 15-minutes. If the TT drains completely, the duration of the second replicate can be reduced to 5 minutes. Otherwise, a second 15-minute replicate should be completed. If the infiltration rate varies significantly between the first and second replicates, additional replicates should be completed until the infiltration rate is relatively stable. The infiltration rate of the final replicate should be reported. A single field technician can complete multiple simultaneous TT setups if multiple devices are available.

The measured value at each TT setup should be divided by 3 to correct for the systemic bias of the device in sand, loamy sand, and sandy loam soils. The corrected field measurements should be aggregated using the Weiss & Gulliver effective K_{sat} to characterize the infiltration rate of the area. The TT should be considered qualitative in fine textured soils.

4.4 TURF-TEC IN2-W LIMITATIONS

The Turf-Tec was observed to be highly susceptible to local heterogeneities in the soil such as macropores. At a small number of TT setups in the swales, it was observed that the inner ring and outer ring drained at different rates with one ring draining several inches of water more than the other. In cases where the rings are clearly draining at different rates, the TT should be moved to a nearby location and the test restarted.

As seen in Figure 3.3, the TT does not effectively measure low infiltration rates soils. As seen in Table 4.1, the accuracy of the TT is poor in fine soils. The finest gradation on the Turf-Tec scale is 1/16 inch. If a Turf-Tec replicate is run for 15 minutes, and the smallest measured drop is half the finest gradation, the smallest infiltration rate that can be measured is 0.125 in/hr (0.32 cm/hr). Most infiltration SCMs will infiltrate water at a rate greater than this rate, and one that infiltrates water slower than this rate will likely be considered unacceptable. The TT should be considered qualitative in fine soils with use limited to comparative purposes.

The Turf-Tec scale is read by observing the position of the head of a screw moving along the scale. The screw head does not have a high precision means of indicating where on the scale the measurement should be read. As such, the Turf-Tec, therefore, should not be considered a high precision device.

The inner ring of the TT infiltrometer is 2-3/8 inch (6.03 cm). Lang (1993) found a column diameter to media grain size diameter ratio of 50:1 was recommended to reduce variability and limit the wall effects in water treatment column pilot studies. A similar ratio seems reasonable for infiltration measurements. This would indicate the Turf-Tec infiltrometer is limited to soils with a grain size smaller than 0.05 inch (1.2 mm), roughly corresponding to a coarse sand.

CHAPTER 5: INFILTRATION RATE MEASUREMENT PROTOCOL

Prior to design, an estimate of the hydraulic conductivity must be known both at the future location of the bottom of the proposed practice (which may be below the existing ground surface), where infiltration through the soil surface will occur, and at depths below the future soil surface to ensure that there are no underlying confining soil layers that could prevent sufficient infiltration. Immediately post-construction, hydraulic conductivity must be determined to verify that the practice was constructed as designed and will infiltrate water once in operation. Finally, to ensure the long-term effectiveness of the practice, the infiltration capacity and/or hydraulic conductivity must be tested periodically in the future so that scheduling and frequency of maintenance activities can be optimized. To optimize the design and continued long-term operation of infiltration-based stormwater management practices, the ability of the soil to infiltrate and pass water through the sub-surface must be known.

Field techniques that measure or estimate the hydraulic characteristics of soil by infiltration processes are, by definition, called infiltrometers. When an infiltrometer is used, water is allowed to pass through the soil surface into relatively dry soil. By measuring the amount or depth of water infiltrated as a function of time, the hydraulic conductivity of the soil can be estimated. Permeameters, by definition, measure the hydraulic conductivity of a soil mass below the soil surface. Either infiltrometers or permeameters can be used in the field to determine the soil hydraulic properties necessary to help ensure the successful design and long-term operation of infiltration-based stormwater management practices.

It is often beneficial to characterize the hydraulic parameters of a soil below the existing soil surface. During construction when excavation equipment is on site, it may be possible to excavate the existing soil down to the desired level and use an infiltrometer on the surface of the newly exposed soil. Alternatively, if excavation is not possible or desirable, a bore hole can be augered to the desired level and a permeameter used at that depth. Both infiltrometers and permeameters have benefits at different phases of the infiltration SCM life cycle. If the current soil surface is not the surface where infiltration rates are desired, then permeameters are the most useful. For example, infiltration rates may be desired below the surface when an infiltration SCM is being constructed at depth, or the infiltration rate of a lower soil layer is desired. If the effect of the top soil layer on infiltration rate is desired, then infiltrometers are the most useful. For example, when evaluating existing stormwater infiltration practices that may be clogged, the top layer of soil is usually important.

5.1 CHOICE OF INFILTRATION MEASUREMENT METHOD

The following sections describe some common and commercially available permeameters and infiltrometers. In Chapter 3, we discussed four methods for characterizing infiltration rates in the field in detail. This section expands on the findings of Chapter 3 to include additional methods that were identified in the literature. For detailed specifications and instructions for each device, readers should see the corresponding user manual and, if one exists for the device, the ASTM standard.

5.1.1 Guelph Permeameter

The Guelph Permeameter was developed by Reynolds & Elrick (1986) and maintains a constant water head via the Mariotte principle to supply water to unsaturated soil in a user constructed bore hole. Time requirements for a single test depend on the type of soil but usually vary between one-half to two hours. The water volume required per test is approximately two-thirds of a gallon (2.5 liters).

Before using a Guelph Permeameter, a user must first evaluate the soil and site, prepare a bore hole (typically 2.4 inches or 6 cm in diameter), assemble the permeameter, fill two permeameter reservoirs with water (one reservoir may be used for low permeameter soils such as clays), and place the permeameter in the bore hole. Steady discharge from the reservoir(s), each at a different head, is maintained into the bore hole to determine the saturated hydraulic conductivity, matric flux potential, and sorptivity of the soil.

Guelph Permeameters can be used to measure field hydraulic conductivity 6 to 30 inches (15 to 75 cm) below the soil surface. Attachments can be purchased, however, that increase measurement capability up to about 10 feet (315 cm) below the surface. For comparison, Ebrahimi & Moradi (2015) found that the double ring infiltrometer (DRI) method required 4 to 6 times greater volume of water than the Guelph Permeameter method, and the total measurement time using a DRI was approximately two times higher than when using a Guelph Permeameter. There is no ASTM standard for the Guelph Permeameter.

5.1.2 Philip-Dunne Permeameter

The Philip-Dunne permeameter is a falling head device used to estimate saturated hydraulic conductivity. Thomas Dunne and Elizabeth Safran utilized a device that was a cylinder 2.4 inches (6 cm) in diameter and over 12 inches (30 cm) tall to estimate soil properties in the Amazon basin. Philip (1993) developed the theory to estimate Ksat from the Amazon soil measurements. It is typically made of metal or plastic and is inserted into the bottom of a bore hole dug between 2 and 6 inches (5 and 15 cm) into the ground. The initial moisture content of the soil is measured, the cylinder is filled with water to approximately 12 inches (30 cm) in depth, and the time required for the water level to drop to half the height of the cylinder is recorded. The final moisture content of the soil must also be recorded and can often be assumed equal to the porosity of the soil (i.e., the soil is assumed to be fully saturated). The radius of the cylinder, drawdown time, and other measured values are used to estimate the soil suction and the saturated hydraulic conductivity of the soil. There is no ASTM standard for the Philip-Dunne Permeameter, although the Modified Philip-Dunne infiltrometer described below in section 5.1.7 does have an ASTM standard.

5.1.3 Single Ring Infiltrometer

Single ring infiltrometers have been used for some time. The earliest found references to single ring infiltrometers occurred in the early 1950s (Bower, Swarner, Marsh, & Tileston, 1951; Stirk, 1951), although it was probably used earlier. Reynolds & Elrick (1990) completed extensive work developing and improving the theory to evaluate data collected using single ring infiltrometers. The current, typical single ring infiltrometer consists of a 11.8-inch (30 cm) diameter ring that is 7.9 inches (20 cm) tall and can be used as either a constant head or falling head device. Metal single ring infiltrometers can weigh 35 lbs (15.6 kg). The ring is driven approximately two inches (5 cm) down into the soil and water is poured on the soil surface to fill the ring. Typically, a minimum of five gallons (19 liters) of water is required per test. In the constant head method, the flow of water to the ring is measured and used to calculate the saturated hydraulic conductivity of the soil. The method assumes that all flow within the soil is vertically downward when, in fact, some spreads laterally. The single ring infiltrometer therefore tends to result in overestimated values of saturated hydraulic conductivity. There is no ASTM standard for the single ring infiltrometer.

5.1.4 Double Ring Infiltrometer

The double ring infiltrometer has also be used for some time (Burgy & Luthin, 1956). It is often considered to be the industry standard device. It is simple to understand but can be difficult to implement. The double ring infiltrometer is a constant head device (ASTM International, 2018c) that consists of two concentric cylinders of 12 inches (30 cm) and 24 inches (60 cm) in diameter. Both rings are continuously filled with water to maintain a constant water level as water infiltrates into the soil. The purpose of the outer ring is to reduce lateral movement of water that has infiltrated through the inner ring, thus making the assumption of no lateral flow more accurate. A single test can require 2 to 164 gallons (7.3 to 620 liters) and ASTM (2018c) recommends a test duration of 6 hours, although some guidance allows for test durations to be shortened to two hours (Wisconsin Department of Natural Resources, 2017).

The rings, which weigh a combined 50 pounds (22.7 kg), must be pushed into the ground using an eight-pound (3.6 kg) hammer. Compacted soils often require the double ring infiltrometer to be jacked into the ground, which may be difficult or prohibited. With water supplied at a constant head to both rings, the infiltration rate is measured as a function of time. When the infiltration rate is close to steady state, the rate is assumed to be equal to the saturated hydraulic conductivity of the soil. Limitations of this method exist due to the size and weight of the device and the relatively large volume of water required per test. For this reason, many applications utilize a double ring infiltrometer that is smaller than the ASTM size (Gregory et al., 2005; Lai, Luo, & Ren, 2012; R. Nestingen et al., 2018). Also, because infiltration is not purely vertical even with the second ring, values of saturated hydraulic conductivity tend to be overestimated (Wu, Pan, Roberson, & Shouse, 1997).

5.1.5 Tension Infiltrometer

A tension infiltrometer is a constant head device that can measure unsaturated or saturated soil conditions and assess hydraulic properties of the top layer of soil (Clothier & White, 1981; Soil Moisture Systems, n.d.; Zhang, 1997). Typically, for assessing stormwater infiltration practices, saturated hydraulic conductivity measurements are made. The time requirement of a tension infiltrometer test is typically 1.5 hours.

The tension infiltrometer includes a four or eight-inch (10 to 20 cm) diameter porous disc connected to a Mariotte bottle. The porous disc is placed on the soil surface, typically after vegetation and debris has been removed. Also, a thin layer of sand is often placed between the soil and disc to help maintain good contact between the two. By maintaining a small negative pressure (i.e., tension) on the water as it leaves the infiltrometer, water infiltrates at a slower rate than when water is allowed to pond freely on the soil surface. When water is ponded on the soil surface when using other devices, the water may infiltrate through cracks in the soil or worm holes, etc. and measurements can reflect soil structure in addition to the texture of the soil matrix. The negative pressure maintained by a tension infiltrometer reduces flow into cracks and worm holes and, therefore, results may more accurately reflect properties of the soil matrix.

The procedure involves performing tests at two different tension values and using the results to calculate soil hydraulic properties. To estimate the saturated hydraulic conductivity of a soil, the tensions used must be zero and near zero (e.g., -2 inches and -0.4 inches). Data may be collected manually or automatically using a data logger. By using data loggers, an individual may run multiple tests concurrently. Data collection involves recording the water level in the supply reservoir and the time elapsed since the start of the test. There is no ASTM standard for tension infiltrometers.

5.1.6 Mini Disc Infiltrometer

The Mini Disc Infiltrometer is a small version of a tension infiltrometer and, thus, its operation is similar (Meter Group, n.d.). Due to its smaller size, it is usually more convenient to transport the device and necessary water volumes to test sites. Its base is 1.77 inches (4.5 cm) in diameter, the total height of the device is 12.9 inches (32.7 cm), and its required water volume for one test is approximately 0.03 gallons (135 mL).

Similar to the tension infiltrometer, the Mini Disc Infiltrometer applies a constant head at a small negative pressure (i.e. tension) and the water level in the reservoir is recorded at regular time intervals until the reservoir is empty. The time interval between recordings depends on the tension value used for the test and the type of soil and ranges from two to five seconds for sand and 30 to 60 minutes for clays (Fatehnia, Tawfiq, & Abichou, 2014). There is no ASTM standard for the Mini Disc Infiltrometer.

5.1.7 Modified Philip-Dunne Infiltrometer

The Modified Philip-Dunne Infiltrometer was first used by Nestingen (2007) and Asleson et al., (2009), and is described in detail by Ahmed et al., (2014). It is a 19.7-inch (50 cm) long, 3.9 inch (10 cm) diameter vertical cylinder that is inserted 1.9 inches (5 cm) into the soil surface. As the name implies, it is the surface version of the Philip-Dunne permeameter described above in section 5.1.2. An ASTM standard exists for the Modified Philip-Dunne Infiltrometer (ASTM International, 2018b), although an ASTM standard does not exist for the Philip-Dunne permeameter. When used, water is poured into the cylinder at the beginning of the test and water surface elevation within the cylinder is recorded as a function of time. The moisture content of the soil before and after the test must be determined or estimated. The analytical methods described in the ASTM, that assume the water infiltrates as a capped sphere, can be followed to estimate the saturated hydraulic conductivity or a proprietary computer program can be used (Upstream Technologies, 2017).

A single test typically requires 30 to 60 minutes and two-thirds of a gallon (2.5 liters) of water, and one field technician can operate multiple Modified Philip-Dunne Infiltrometers simultaneously. Commercially available Modified Philip-Dunne Infiltrometers can collect data automatically and, if multiple devices are owned, dozens of tests can be completed in one day.

5.1.8 Turf-Tec Infiltrometer

The Turf-Tec Infiltrometer has been used in the turf-management industry (Turf-Tec International, n.d.-a). It has an inner ring diameter of 2-3/8 inches (6.03 cm) and an outer ring diameter of 4.25 inches (10.79 cm). The unit weighs 12 lbs (5.5 kg). The device is simple to use and the method to calculate results is intuitive. The Turf-Tec can be easily inserted into the soil and the water requirement is minimal at approximately one-third of a gallon (1.25 liters) per test. The time required for a single test is approximately 15 minutes, with tests repeated two or three times to moisten the soil. Like the Modified Philip-Dunne infiltrometer, one field technician can operate multiple Turf-Tec devices simultaneously. The Turf-Tec Infiltrometer also assumes one-dimensional vertical flow, which tends to result in an over estimation of saturated hydraulic conductivity values. Since the Turf-Tec is smaller than other devices, its uncertainty relative to the performance of the infiltration practice is likely larger due to the small volume of water used and the possibility of macropores creating a high infiltration rate. Also, the Turf-Tec Infiltrometer does not have an ASTM standard.

5.1.9 Pit Test

There are a few types of pit tests accepted by various state stormwater programs. Most are similar to the City of Seattle’s test, which will be described here: a) dig a 2 ft diameter, 2 ft deep hole in the infiltration practice, b) fill water to the 12 in deep mark, c) keep the water depth at that depth for 30 minutes, d) record the fall in water level for 1 hour, e) record the water depth for the second hour. The smaller of the two infiltration rates is the recorded infiltration rate.

5.1.10 Soil Classification of Borehole Texture

The ASTM soil classification system (ASTM International, 2018a) can be used with the Minnesota Stormwater Manual (Minnesota Pollution Control Agency, 2017a) to estimate an infiltration rate or saturated hydraulic conductivity of the soil. In this process, the soil texture is classified according to the ASTM standard. With the soil texture identified, the Design Infiltration Rates table in the Minnesota Stormwater Manual, which is based on Rawls et al., (1998), is used to estimate an infiltration rate. An ASTM standard to estimate an infiltration rate or hydraulic conductivity value based on the soil classification does not exist.

This method is approximate because a given soil classification often has a wide range of potential saturated hydraulic conductivity values. The saturated hydraulic conductivity of a soil can vary, often widely, over a short distance. This method does not capture as much of the soil heterogeneity as the other devices and can underestimate conductivity and infiltration values because it does not incorporate the effects of worm holes, roots of vegetation, etc., which tend to increase infiltration and conductivity.

5.1.11 Summary of Devices

This section presents a brief overview of the previously discussed devices that are available for estimating the infiltration rate and/or saturated hydraulic conductivity of a soil. For more detailed information and corresponding user instructions, please see information provided by the manufacturer of a specific device and any relevant published ASTM standard. A summary of the available devices covered in this section is shown in Table 5.1.

Table 5.1 Summary of devices to measure infiltration capacity or hydraulic conductivity

	Test Method (Constant or Falling Head)	Water Volume Required	Test Area (in^2)	Time Required	Advantages (Adv)/Disadvantages (Dis) and Comments
Guelph Permeameter	Constant	0.67 gal (2.5 L)	4.4	0.5 - 2 hrs	Adv: Relatively accurate. Dis: Does not include impact of soil surface, relatively large volume of water required, and potentially large time required to reach steady state. Requires measurement of variable flow rate to maintain two different constant heads.
Tension Infiltrometer	Constant	0.2 - 0.6 gal (0.8 - 2.1 L)	7.8 or 48.7	0.25 - 0.5 hrs	Adv: Includes impact of soil surface, can be used to measure unsaturated hydraulic conductivities. Dis: Requires measurement of variable flow rate to maintain two different constant heads.
Mini Disc Infiltrometer	Constant	0.03 gal (0.135 L)	2.5	A few seconds to an hour	Adv: Small, easy to transport, low water volumes required, incorporates impact of soil surface. Dis: May be difficult to provide good contact with soil surface.
Single Ring Infiltrometer	Constant or Falling	5 gal (19 L)	109.3	2 - 6 hrs	Adv: Smaller than double ring infiltrometer, incorporates impact of soil surface. Dis: Tends to overestimate saturated hydraulic conductivity, large times and volumes of water may be required, must measure variable flow rate, must maintain constant head.
Double Ring Infiltrometer	Constant	2 - 164 gal (7.3 - 620 L)	109.3	2 - 6 hrs	Adv: Often considered the industry standard, includes impact of soil surface, an ASTM standard exists. Dis: Tends to overestimate saturated hydraulic conductivity, large times and volumes of water may be required, must measure variable flow rate, must maintain constant head in both rings, may be difficult to push into soil.
Philip-Dunne Permeameter	Falling	0.2 gal (0.8 L)	1.5	30 - 60 minutes	Adv: Relatively small, small volume of water required, multiple tests can be performed in one day. Dis: Tends to overestimate saturated hydraulic conductivity, must determine soil moisture before and after a test.

	Test Method (Constant or Falling Head)	Water Volume Required	Test Area (in^2)	Time Required	Advantages (Adv)/Disadvantages (Dis) and Comments
Modified Philip-Dunne Infiltrometer	Falling	0.66 gal (2.5 L)	12.2	30 - 60 minutes	Adv: Relatively small, small volume of water required, multiple tests can be performed in one day, lateral flow is incorporated into solution process so less likely to overestimate saturated hydraulic conductivity, an ASTM standard exists. Dis: Must estimate soil moisture before and after a test.
Turf-Tec Infiltrometer	Falling	0.3 gal (1.25 L)	4.5	15 min/test, 2 test min.	Adv: Small, easy to use and insert in the soil. Dis: Due to its small size large errors are more likely due to not capturing soil variability, may overestimate saturated hydraulic conductivity.
Seattle Pit Test	Falling	25 – 75 gal (91 – 274 L)	453	2,5 hours	Adv.: No specialized equipment required. Dis.: Tends to overestimate saturated hydraulic conductivity, large times and volumes of water required.
Soil Classification	N/A	N/A	1.8	0.5 – 6 hours	Adv: Soil borings can often be completed with other geotechnical investigations. Dis: Infiltration rates are based on averages in the literature rather than site-specific values.

5.2 DEVICE SELECTION

A first step in determining the hydraulic characteristics of soil in an existing or future infiltration-based stormwater management practice is to select the device to be used. This selection may be heavily influenced by previously purchased and available devices and the level of comfort and experience that those who will use the selected device already have with certain equipment. Other factors as discussed below, however, should be considered in the selection process.

Users should consider site access, distance to water, the time required to complete data collection, the ease of transporting devices, the volume of water required per test, the total number of tests to be completed, and the accuracy and complexity of data collection and analysis. Device selection must balance the long-term goals of all current and future projects with practicality, time, and cost. Access to the site with the necessary equipment needs to be considered. The device (or multiple devices if so chosen) must be transported to and from the site and installed at the site. The volume of water required to complete all tests must be available on site or be transported to sites with consideration of the distance to a water source. The number of tests to be performed and the time required for each device to complete a single test, coupled with any plans to run tests simultaneously must also be considered.

To gain an understanding of how soils at a site vary spatially and to limit uncertainty of results, multiple tests will often be advantageous or required. In these cases, smaller devices with low water volume requirements, which can be run by a single user are typically most convenient. Of course, device selection is ultimately a unique decision that results from a unique set of goals that must be balanced with device cost, efficiency, cost of labor, available time, desired accuracy, and other factors. Thus, device selection must be done on an individual or organizational basis and the best device for one organization may not be the best device for another organization, even under what appear to be similar circumstances.

All the infiltration measurement methods evaluated herein measure the infiltration in a given volume of soil. Consideration should be given to the volume of soil used by the infiltration SCM and the volume of soil measured by each infiltrometer or permeameter. Assessing the infiltration potential throughout the vertical soil profile may be necessary to avoid adverse impacts from confining layers or groundwater interactions.

5.3 PREPARATION FOR SITE VISIT

To conduct soil tests effectively and efficiently, detailed planning prior to traveling to the site and performing the tests must be completed. This section details that planning and provides corresponding guidance and recommendations.

5.3.1 Safety

Safety is always a priority. If working with a local organization with safety protocols already established, plan to follow those protocol at a minimum. Automobile traffic is a particular concern, safety vests should be worn, and vehicles should be well out of the traffic path. If moving vehicles out of the traffic path is not possible, a vehicle with warning lights should be utilized. Gopher one should be called when going underground with a permeameter or a pit.

5.3.2 Number of Tests

The number of infiltration tests required to characterize an area is based on the required level of confidence, the standard deviation of the distribution, and the acceptable margin of error. A detailed discussion on selecting the number of tests is included in Section 3.2.

5.3.3 Location of Tests

With the number of tests to be conducted per area of consistent soil characteristics determined, one must also determine where the tests will be conducted within each of those areas. It is recommended to determine the location of individual tests in planning phase so that, once at the site, the locations only need to be marked.

In general, test locations should be equally spaced from other test locations within an area of consistent soil characteristics. This recommendation is consistent with guidance from Ahmed et al., (2015). For efforts that involve three or fewer tests per area of consistent soil characteristics in a non-linear area (i.e. infiltration basins with length to width ratio of less than 3:1), the test locations should be selected so that the locations are approximately equal distance from each other and that same distance from the closest edge of the area being tested. For linear areas (i.e. roadside swales) with three or fewer tests, locations should be equally spaced along the length of the area with locations being approximately equidistant from each long side of the area. Also, in this case, the distance from the end of a linear area to the nearest test location should be approximately half of the distance between two test locations.

For efforts that include four or more tests per area of consistent soil characteristics, two to five test locations should be equally spaced across the width of the area at one location. This process should be repeated at equally spaced distances along the length of the area (i.e., longitudinally). The distance from the first and last longitudinal locations to the closest end of the area should be approximately one-half the distance between longitudinal locations (see example that follows).

Initial clogging in infiltration practices often occurs at or near the low point in the practice. This occurs because the low portion is the most active area of infiltration within in the practice. The reason is that for even very small runoff events, water (and any sediment carried by the water) accumulates near the low point. Higher locations in the practice only infiltrate water and filter solids during larger events. As a result, the lowest areas within the practice fill with sediment and clog more quickly than other locations within the practice. Thus, when determining the location of tests, it is important to adequately represent the low areas in the practice.

5.3.4 Water Supply

There must be enough water present to conduct the number of desired tests per site visit. If water is available at the site by means of a faucet, fire hydrant, nearby water body, water tank on a trailer or truck, or other source; water may not need to be transported to the site, but enough adequately sized containers are still required. Permission to use water from sources at or near the site may be necessary and, if so, should be obtained in writing prior to testing.

With a device selected,

Table 5.1 can be used to estimate the water volume required per test. With the number of required tests known, the total volume of water required can be determined. As a factor of safety, it is recommended to increase the total volume of water required by 10 to 20%.

5.3.5 Number of Devices

The number of testing devices used per site visit must be determined. This number may appear to be limited by the number of devices owned or that are available at the time of testing. Careful consideration, however, should be given to purchasing additional devices, if needed, to optimize efficiency and reduce total costs. Total costs include the cost of the devices, labor, transportation to and from sites, and other factors. For example, if two people can operate multiple devices simultaneously but only one device is owned, it may be cost-effective to purchase additional devices so that the total time spent, and therefore labor costs associated with, conducting tests is reduced. The number of devices needed is also linked to the number of people who will perform the tests.

5.3.6 Number of People

The number of people sent to a site to perform tests should be selected to optimize cost-effectiveness between labor costs, time, safety, and other variables and will depend on the testing device selected and the number of tests to be conducted per site visit. Two people is typically the minimum for safety purposes. For larger devices, devices that cannot be run simultaneously, or are complicated to set-up and use, a third person may not only be more cost-effective, it may be necessary.

Due to the large number of variables involved, the optimum number of people used to conduct tests per site visit will vary on a case-by-case basis and per organization. Thus, for each site visit, the number of people to deploy to conduct tests must be uniquely decided by considering all relevant variables.

Individuals who will perform the tests should have read all corresponding user manuals and, if applicable, corresponding ASTM standards. A photocopy of the relevant portions of the user’s manual should be made and taken with the individuals into the field. They should also, if needed, practice setting up the device and perform one or more tests prior to starting testing.

5.4 AT THE SITE

Once at the site, the following steps can be taken to collect necessary data that will enable the hydraulic properties of the soil to be estimated. A field manual that can be used as a reference document to guide the individual completing infiltration measurements throughout the testing process while on site is provided in Appendix D. The field manual is intended to be used in conjunction with the information provided in this chapter, and to be used for quick reference in the field.

5.4.1 Mark All Test Locations

Remember that areas with different soil characteristics (i.e., soil type, texture, level of compaction, or surface cover) should be tested independently of other areas. The number of tests to be conducted for each area of consistent soil characteristics and the location (e.g., coordinates) of each test within those areas should have been previously determined in the planning phase.

One of the first things to do upon arrival at the site is to mark each test location. Markers can be small flags, sticks, or other items. Using GPS, surveying equipment, or other means, the physical field location of each test must be determined on site and marked.

5.4.2 Perform Tests and Collect Data

Once test locations have been determined and marked on site, testing can begin. If the investigation is pre-construction, it is important to perform each test at an elevation that corresponds to the future bottom of the infiltration-based stormwater treatment practice or, alternatively, at an elevation below the bottom of the proposed practice. If infiltration measurements are needed below the surface, an infiltrometer can be used in an excavated area, or a permeameter can be used in a bore hole. If the investigation is during construction or post-construction and all earthwork associated with the practice has been completed, a permeameter can be used in the same manner as described above to measure hydraulic conductivity below the soil surface. Alternatively, an infiltrometer can be used at the exposed soil surface without any excavation.

The following steps should be taken to complete testing:

1. Any necessary earthwork should be completed.
2. Water must be transported to the test location(s). Devices and accessories must also be transported to the test location(s). If tests are to be run simultaneously, multiple test locations can be prepared before any tests begin. Alternatively, simultaneous tests can be prepared after previous tests are underway. This decision is based on individual preferences and experience.
3. The device at each test location should be set up according to relevant user manuals and, if any exist, ASTM standards. The ground surface should be prepared (if necessary), and all testing and data collection should be initiated in accordance with corresponding documents. Any deviations from planned site activities should be logged in data books and photographed for reference. Detailed logs need to be made of the infiltration tests and photographed for reference.
4. Once test procedures at a given location have been completed, full and correct data collection should be confirmed. If possible, check to make sure that collected data appears reasonable and all expected data has been recorded. If anything appears amiss, the test should be repeated.
5. The above steps should be repeated for all test locations planned for the site visit.

5.4.3 Site Visit Wrap-Up

The site should be left as it was before the infiltration tests. Any soil removed in preparation for the tests should be replaced. The site must be left so that it is safe for people and animals, even if none are expected on the site. Collect and clean all devices, computers, equipment, data books, tools and any other items transported to the site and pack them for return transport. If water was gathered onsite from a faucet, fire hydrant, or other similar sources, the water supply must be turned off and returned to its original condition.

5.5 FIELD MEASUREMENT RESULTS

This section is not intended to describe how to analyze the raw data from selected devices. Rather, it is assumed that each user has and can follow instructions to process field data so that experimental values of saturated hydraulic conductivity and/or infiltration capacity can be determined. This section addresses what can be done with those results.

5.5.1 Individual Data Points

Results for each test location can be considered individually. Typically, infiltration-based practices have an expected design or operating range of infiltration capacity and/or saturated hydraulic conductivity. If the testing is performed prior to design or construction and results fall outside the expected range, serious consideration should be given to moving the stormwater management practice to another location.

If the testing was performed during construction or anytime post-construction, any test locations that have resulting parameters that fall below their expected range should be subject to further consideration, investigation, and/or maintenance because they are likely clogged or were compacted. In this case, maintenance actions should be considered. Situations in which maintenance may not be warranted include when the rest, or most, of the test locations within the practice are operating within expected ranges and, overall, the practice is operating as expected.

If the testing was performed during construction or anytime post-construction, individual locations with parameters that fall above the expected range should be subject to maintenance because they are passing water at excessive rates and the filtering and biological cleaning mechanisms typically provided by the soil may be bypassed.

5.5.2 Overall Effective Saturated Hydraulic Conductivity

Hydraulic properties of a soil can vary widely throughout a soil mass even at locations that are relatively close to each other and in soil that appears to be homogenous to the eye. This is true even for a uniform engineered soil of a stormwater management practice. The individual results can be aggregated to give an indication of the overall performance of the practice as an effective saturated hydraulic conductivity. Investigation by Weiss & Gulliver (2015) revealed that a more accurate estimate of an effective overall K_{sat} value for infiltration in a practice is obtained by taking a weighted average of the arithmetic mean ($\bar{x}_{ari}$) and the geometric mean ($\bar{x}_{geo}$), rather than either mean by itself. The expression for the effective overall saturated hydraulic conductivity, $K_{sat\text{-}eff}$, is given by Equation 5.1.

Equation 5.1

$$K_{sat-eff} = 0.32 * \bar{x}_{ari} + 0.68 * \bar{x}_{geo}$$

Values of $K_{sat\text{-}eff}$ can be used to estimate and/or model the performance of an infiltration-based stormwater practice. With this assumption the practice is assumed to be homogenous with a single value of Ks that is equal to $K_{sat\text{-}eff}$. This results in a much simpler analysis than using multiple values of K_{sat} that vary throughout the practice.

CHAPTER 6: CONCLUSIONS

6.1 DISCUSSION

Infiltration SCMs are an important structural practice that can aid in mitigating the adverse impacts of urbanization on stormwater water quality and quantity. Infiltration SCMs attempt to mimic those natural hydrologic processes of infiltration and evapotranspiration, processes that are not well represented in the water budget of filtration or detention structural stormwater practices. However, infiltration SCMs have a high failure rate in the range of 10% to 50%, which reduces their efficacy and limits the adoption in engineering practice. The goal of this research is to provide the information required to reduce existing knowledge gaps, thus increasing the likelihood that infiltration SCMs can be successfully constructed.

A review of the literature and existing state stormwater manuals found substantial variability in the available guidance. This variability was interpreted to mean that a consensus on the best methods has not yet been attained. States consider numerous methods of measuring in-situ saturated hydraulic conductivity to be acceptable, without providing a basis for this acceptance. Many states allow a single infiltration measurement to be used to characterize an area, while the literature has shown K_{sat} is a log-normally distributed variable that can span two orders of magnitude over the spatial scale of small infiltration SCMs.

Practitioners in Minnesota were interviewed to determine how the current guidance is being implemented on construction projects. Practitioners indicated the importance of identifying potential infiltration areas early in the design phase to allow the area to be integrated with other design elements. It was also noted that pre-design infiltration rates were typically determined based on soil texture rather than in-situ infiltration measurements. This research focused on providing practitioners tools that would assist in identifying sites likely to be successful prior to field investigation, then guidance on how to conduct field investigation to assess the in-situ infiltration rates. The guidance to evaluate infiltration rate is also applicable to construction quality control and post-construction maintenance assessments.

The Preliminary Infiltration Rating (PIR), described in Chapter 2, was developed as a geographic information system (GIS) method to identify areas that are likely able to support surface infiltration SCMs. The PIR generates a “heat map” by aggregating four variables that are readily available from online sources. The “heat map” can be overlaid with other relevant project data, including environmentally sensitive areas, property information, and proposed infrastructure, to identify the areas that are most likely to be suitable for surface infiltration SCMs. The PIR aggregation method was calibrated and validated using rain garden maintenance inspections in Anoka County, MN. The validation resulted in the PIR predicting an accurate or conservative infiltration performance estimate in 85% of rain gardens. Once automated, the PIR can be calculated in approximately 2-4 hours, providing a consistent method for assessing large project areas. The PIR can also be used as a communication tool between technical and non-technical project partners.

The Modified Philip-Dunne (MPD) infiltrometer, double ring infiltrometer (DRI), Turf-Tec (TT) infiltrometer, and soil texture (ST) methods of evaluating in-situ infiltration potential were evaluated in roadside swales as discussed in Chapter 3. The site-specific point measurements, that is MPD, DRI and TT, were found to capture the spatial heterogeneity better than using ST to predict infiltration rate. The accuracy of the four methods could not be assessed because calculations of the actual infiltration rate of the swales by other parties had not been completed. The variability in K_{sat} was found to be high, indicating that multiple point measurements need to be completed regardless of the method. The number of point measurements required to characterize a given area is a function of the required level of confidence, the standard deviation of the distribution, and the acceptable margin of error.

The Turf-Tec has been widely used in the turf-management industry but has not been widely used in engineering applications. The Turf-Tec did not have an ASTM standard, and there was limited information in the literature on the application and accuracy of the measurement. The Turf-Tec is a small, lightweight, rapid test that has a low water volume requirement. Therefore, a large number of Turf-Tec measurements can be completed relative to the double ring infiltrometer for the same personnel hours or required water volume. This may be useful in characterizing the infiltration potential and variability of an area, such as in construction quality control. Chapter 4 investigated the non-conservative systemic bias of the Turf-Tec introduced by the small size of the rings and simplifying assumptions of the method. To correct this systemic bias, it is recommended to divide the measured rate by a factor of 3 in sands, loamy sands, and sandy loams. While the Turf-Tec has potential to test surface infiltration rates in coarse soils typical of infiltration practices and engineered media, the non-conservative error is even larger in fine textured soils. The Turf-Tec results should be considered qualitative in fine textured soils.

The infiltration measurement methods that were evaluated in Chapter 3 and Chapter 4 and were developed into a measurement protocol using most known infiltrometers and permeameters for assessing a site in Chapter 5. The protocol allows for the selection of the most appropriate field method for the situation. The results can be analyzed individually or in aggregate. Reviewing individual point measurements can aid in identifying areas that may be in need of maintenance. Reviewing the results in aggregate using the Weiss and Gulliver (2015) effective K_{sat} can be useful in determining a single value that characterizes the area. The protocol is applicable to all phases of an infiltration SCM life cycle including during design, construction quality control, and post-construction maintenance assessments.

6.2 APPLICATION TO LAND DEVELOPMENT

This research is intended to be directly implementable by practitioners looking to manage stormwater as part of the land development process. The research is applicable to projects in transportation, municipal engineering, site development, and other land disturbing activities. The PIR can be used to identify potential locations for an infiltration SCM early in the planning or design phase and can be used to communicate those decisions between stakeholders. The infiltration measurement protocol can be used with the field method of choice to verify the infiltration potential during the site investigation. The protocol can also provide guidance during construction quality control and post-construction maintenance. Information is provided to assist practitioners in selecting the appropriate field method for measuring infiltration potential.

6.3 LIMITATIONS

The PIR is based on data sets, each with their own uncertainty. Notably the soils data sets have high spatial and temporal variability. A thorough understanding of the underlying data sets is important for understanding the predictive ability of the PIR.

All the infiltration measurement methods evaluated here measure the infiltration in a given volume of soil. Consideration should be given to the volume of soil to be used for infiltration and the volume of soil measured by each infiltrometer. Assessing the infiltration potential throughout the vertical soil profile may be necessary to avoid adverse impacts from confining layers or groundwater interactions.

All soil hydraulic properties are subject to spatial and temporal variability. Therefore, measuring a true value would require continuous monitoring of the entire soil volume. As this is not often practicable, infiltration measurement replicates are necessary for all discussed methods. The number of measurements, variability in measured data, level of confidence, and the margin of error are all interrelated, and any one variable can be calculated from the other three.

6.4 BENEFITS

The MPCA Construction Stormwater General Permit requires all projects that create 1 or more acre of new impervious surface, including projects that create less than 1 acre but are part of a larger common plan of development, to treat a water quality volume (WQV). For non-linear projects, this water quality volume is equal to 1 inch multiplied by the sum of the new and fully reconstructed impervious surface. For linear projects, the water quality volume is calculated as the greater of 1 inch multiplied by the new impervious surface, or 0.5 inch multiplied by the sum of the new and fully reconstructed impervious surface (Minnesota Pollution Control Agency, 2020). A project that creates 1 acre of new impervious surface would therefore require 3630 cubic feet of water quality volume. An infiltration trench would be a SCM option for meeting the required WQV that typically works well with many transportation projects. Weiss et al. (2005) suggests that an infiltration trench would cost about $8.50 per cubic foot of WQV in 2005 dollars, excluding the cost of land. A consumer price index conversion from 2005 dollars to 2021 dollars would increase the cost to approximately $11.70 per cubic foot of water quality volume. Therefore, each new acre of impervious surface requires approximately $42,000 dollars of construction cost to meet the required WQV, excluding the cost of land. The average cost of Minnesota agricultural land in 2021 is approximately $5,000/acre (U.S. Department of Agriculture National Agricultural Statistics Service, 2019), so a typical cost of treating an additional acre of impervious area is $47,000.

The Minnesota Department of Transportation (MnDOT) has estimated the failure rate of infiltration practices to be between 15% and 30% of all installed SCMs (CTC & Associates LLC, 2018). MnDOT reported construction of more than 100 infiltration SCMs over the last 10 years (CTC & Associates LLC, 2018), and recent water quality regulations require that a volume reduction practice such as an infiltration practice should be the first consideration.

For the five years between 2013 and 2017, MnDOT expended approximately $500 million on road construction projects and road safety projects that included additional impervious surface (Minnesota Department of Transportation, 2018b), or $100 million per year. At roughly $500,000 per lane mile (Minnesota Department of Transportation, 2018a) and 1.5 acres per lane mile there were roughly 300 acres of impervious surface constructed per year that would be required to meet water quality regulations. Approximately half of the applications will not have an underlying soil with sufficient infiltration rate (where an infiltration SCM is not feasible), and of those constructed, it is estimated that 15% will fail initially (CTC & Associates LLC, 2018). Thus, the benefits of this research to MnDOT are estimated as follows:

$$\frac{Benefits}{year} = \frac{\$47{,}000}{acre}\ 300\,\frac{acres}{year}\ 0.5\,\frac{inf}{total}\ 0.15\ \frac{failure\ rate}{inf} = \frac{\$1{,}060{,}000}{year}$$

Similar benefits would accrue to counties and cities that may have many lane-miles under construction. The project is also intended to increase designer confidence in infiltration practices and provide a common framework for designers around the state. The protocols for pre-design site evaluation and site-specific soil testing should provide a robust framework for designing functioning infiltration SCMs. MnDOT staff members who are confident in the success of the project are likely to be more successful in coordinating with adjacent property owners who have concerns about the potential for a failed infiltration practice. An increase in designer confidence is likely to result in more infiltration practices being constructed, rather than designers selecting water quality SCMs that do not reduce runoff volume such as filtration basins, wet detention ponds, or similar SCMs. An increase in groundwater recharge leading to a reduction in surface water runoff and associated pollutants would be a benefit to Minnesota waterways and all residents.

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APPENDIX A
GIS PROCEDURE FOR PIR

General:

1. Identify study boundary
2. Unless otherwise noted, data is available through Minnesota Geospatial Commons (https://gisdata.mn.gov/)

Identify Areas of Infiltration Prohibitions:

1. Create polygon feature class for infiltration prohibitions (INF_Prohibit)
    a. The combination of polygon features will represent the spatial extent of the area where infiltration is likely to be prohibited
2. Import National Wetland Inventory data available
    a. Copy any wetlands within study boundary to INF_Prohibit
3. Import What's In My Neighborhood data
    a. Review available points within and near study boundary to determine if contaminated soil is likely associated with any activities
    b. If contamination is likely, determine probable extent of contamination such as parcel boundary.
    c. Copy spatial extent of likely area of contamination to INF_Prohibit
4. Import depth to bedrock data from Minnesota Geologic Survey Drift Thickness 2016 available through Minnesota Geological Survey's Open Source Data (https://mngs-umn.opendata.arcgis.com/pages/spatial-datasets)
    a. Identify if any areas within the study boundary are in the 0-25 foot depth to bedrock classification
    b. Convert raster to polygon and copy spatial extent of 0-25 foot depth to bedrock to INF_Prohibit
5. Import SSURGO soils data available through USDA (https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx)
    a. Use Soils Thematic Map Tool to identify the Hydrologic Soil Group (HSG) of soils within study boundary
    b. If HSG D is present, copy areas to INF_Prohibit. Note that dual HSG (eg A/D, B/D, C/D) should not be copied to INF_Prohbiit.
6. Import Drinking Water Supply Management Area (DWSMA) and Emergency Response Areas (ERA)
    a. Identify if DWSMA or ERA are within study boundary
    b. Identify appropriate combination of DWSMA and ERA based on desired level of engineering review and MPCA Construction Stormwater General Permit.
    c. A conservative approach if uncertain would be to select all ERA and DWSMA rated moderate, high, or very high.
    d. Copy information to INF_Prohibit
7. Import Karst features
    a. If karst features exist within study boundary, buffer karst features by 1000 feet
    b. Copy buffered polygons to INF_Prohibit

Complete Preliminary Infiltration Rating (PIR) using ModelBuilder tool

1. Obtain SSURGO soil data from web soil survey (https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx)
    a. Use soil thematic map tool to identify saturated hydraulic conductivity (tool is available through USDA: https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/?cid=nrcseprd337066)
    b. Use Aggregation Method "Dominant Component"
    c. Change Layer Option to "All Layers"
    d. Project K_{sat} polygons to desired coordinate system
    e. Save K_{sat} polygons to project geodatabase
    f. It is recommended that an additional feature class is created for soils where K_{sat} information is not available (listed as <Null>). Copy all <Null> polygons to the insufficient data feature class.
    g. Use soil thematic map tool to identify depth to water table
    h. The default options should be "Dominant Component" for Aggregation Method, "Lowest" for tie-breaker, and "January" and "December" as the beginning and ending month, respectively.
    i. Project depth to water table polygons to the desired coordinate system.
    j. Save depth to water table polygons to project geodatabase.
2. Obtain DEM data from MnTopo (http://arcgis.dnr.state.mn.us/maps/mntopo/)
    a. Use 3-meter DEM (if alternative DEM resolution is used adjust Aggregate tool in ModelBuilder as needed)
    b. Project DEM raster to desired coordinate system
    c. Save in project geodatabase
3. Run PIR tool created in ModelBuilder is described by the flowchart in Figure 2.1, based on Equation 2.1, using the weights provided in Table 2.3.
    a. Provide K_{sat}, depth to groundwater and DEM
    b. Save PIR to project geodatabase
4. Adjust symbology in accordance with Table 2.4.
    a. Display insufficient data feature class and INF_Prohibit feature class on top of PIR raster
    b. Display INF_Prohibit feature class on top of the PIR raster
    c. It may be helpful to plot DNR hydrography, study boundary, project centerline, parcel information, or other data sets over PIR raster

APPENDIX B
SOIL PROFILES COLLECTED BY MNDOT AND MPCA

Table B.1 Soil profiles were completed at the I-94 Weigh Station by Dave Bauer and Kellie Thom on June 9, 2017 (Minnesota Department of Transportation & Minnesota Pollution Control Agency, 2017). A summary of the data used in this report is included.

Soil Pit Number	Depth	USDA Texture	Notes
1-1	0" - 6"	Sandy Loam	very compacted
1-1	6" - 16"	Loamy Sand	very compacted
1-2	0-5"	Sandy Loam	very compacted, could not penetrate deeper by using hand tools.
1-3	0-7"	silt loam	very compacted
1-3	7" - 14"	loamy sand	loose
1-4	0 - 7.5"	loam	very compacted, could not penetrate deeper by using hand tools.
1-5	0-12"	loam	very compacted
1-5	12" - 15"	loam	compacted
1-5	15" - 23"	loamy sand	
1-6	0-2"	silty clay loam	sod layer
1-6	2" - 10"	silty clay loam	
1-6	10" - 21"	loamy sand	loose
1-7	0-3"	loam	compacted
1-7	3" - 11"	loam	compacted
1-7	11" - 13"	loamy sand	loose / large rock 40%
1-7	13" - 16"	loamy sand	loose
3-1	0-1"	sandy loam	very compacted
3-1	1"-7"	sandy loam	
3-2	0-1"	sandy loam	very compact, vegetation layer
3-2	1"-12"	sandy loam	very compact
3-2	12"-17"	loamy sand	loose, seems like fill soil
3-3	0-2"	loam	very compacted, vegetation layer
3-3	2"-12"	sandy loam	very compacted, mixed layer

Soil Pit Number	Depth	USDA Texture	Notes
3-4	0-10"	sandy loam	very compacted, roots very shallow
3-5	0-1"	loam	very compact, sod
3-5	1"-10"	loam	very compact
3-6	0-1"	loam	very compact, sod
3-6	1"-15"	loam	very compact
3-6	15"-26"	sand	loose
3-7	0-3"	loam	compact, sod
3-7	3"-20"	loam	compact
3-7	20"-27"	loam	loose

Table B.2 Soil profiles were completed at TH-8 by Dave Bauer and Kellie Thom on June 12, 2017 and by Dave Bauer and Barb Loida on June 16, 2017 (Minnesota Department of Transportation & Minnesota Pollution Control Agency, 2017). A summary of the data used in this report is included.

Soil Pit Number	Depth	USDA Texture	Notes
1-1	0”-3”		asphalt and class 5
1-1	3"-12"	sandy loam	class 5 mixed in
1-1	12"-23"	clay loam	
1-2	0”-7"	sandy loam	
1-2	7"-9"		broken-up asphalt and sand
1-2	9"-22"	clay loam	
1-2	22"-27"	silty clay	
1-3	0”-5"	loam	High Organics
1-3	5"-8"	sandy clay loam	
1-3	8"-19"	clay loam	shale at 12"
1-4	0”-6"	loam	many roots
1-4	6"-21"	clay loam	30% depletions and Crovina
1-4	21"-30"	clay loam	25% gravel
1-5	0-7"	silt loam	
1-5	7"-24"	silt loam	
1-6	0”-4"	silt loam	many roots
1-6	4"-12"	silty clay loam	compacted, dense
1-6	12"-20"	clay	dense
1-6	20"-26"	clay	5% gravel
1-7	0”-5"	silt loam	fiberous
1-7	5”-17"	clay loam	7-11" compacted
1-7	17”-27"	clay	dense layer

Soil Pit Number	Depth	USDA Texture	Notes
5-1	0”-7"	silt loam	
5-1	7”-13"	silt clay	Depletions 5G 4/2 (gley)
5-1	13”-21"	silt clay loam	sand towards bottom
5-1	21”-29"	sandy loam	Redox and depletions
5-2/5-3	0”-4"	silt loam	
5-2/5-3	4”-10"	clay	faint mottles/dep. 5% gravel
5-2/5-3	10”-14"	sandy clay loam	
5-2/5-3	14”-20"	sandy clay loam	10gy 5-1(Gley) 7% dep
5-2/5-3	20”-30"	sandy clay loam	5g 5/1 (gley) 30% dep
5-4	0”-7"	sandy loam	
5-4	7”-18"	sandy loam	
5-4	18”-30"	sandy loam	very narrow band of clay = inclusion
5-4	30”-33"	sandy clay loam	5G1 6/1 2%dep
5-5	0”-7"	loam	
5-5	7”-19"	sandy loam	
5-5	19”-25"	sandy loam	
5-6	0”-5"	silt loam	
5-6	5”-12"	sandy loam	faint mottles and ox rnz.
5-6	12”-17"	clay loam	7% shale
5-6	17”-27"	clay	
5-7	0”-8"	loam	
5-7	8”-18"	clay loam	
5-7	18”-28"	clay loam	5YR 4/6 mottles

Table B.3 Soil profiles were completed at TH-212 by Dave Bauer and Kellie Thom on July 12, 2017 (Minnesota Department of Transportation & Minnesota Pollution Control Agency, 2017). A summary of the data used in this report is included.

Soil Pit Number	Depth	USDA Texture	Notes
1-1	0”-2"	Sandy Loam	A lot of Roots
1-1	2"-18"	Clay	Very Compacted/fill
1-1	18"-22"	Sand	
1-1	22"-32"	Silty Clay	Depletion and clay mixed in
1-2	0”-2"	Sandy Loam	A lot of Roots
1-2	2"-22"	Clay	Fill/very Compact. 2 Colors in Matrix
1-2	22"-28"	Silty Clay	Very Compact
1-3	0”-2"	Clay Loam	Root Layer
1-3	2"-24"	Clay	
1-4	0-3"	Clay Loam	Root Layer
1-4	3"-8"	Clay	
1-4	8"-25"	Silty Clay	
1-5	0”-3"	Clay Loam	Root Layer
1-5	3"-9"	Clay Loam	Mottles
1-5	9"-15"	Silty Clay	Mottles - Old Cattail
1-5	15"-27"	Clay Loam	Redox
1-5	27"-31"	Clay	(Gley) 10%
1-6	0-6"	Clay Loam	10YR 5/2 (Second Matrix)
1-6	6"-12"	Silty Clay	5% Organics
1-6	12"-25"	Clay Loam	15% 10YR 2/1
1-6	25"-29"	Sandy Loam	
1-7	0-6"	Clay Loam	
1-7	6"-17"	Clay Loam	

Soil Pit Number	Depth	USDA Texture	Notes
1-7	17"-29"	Silty Clay Loam	2.5YR 3/6 7%
3-1	0-13"	Silty Clay Loam	Mixed
3-1	13"-19"	Silty Clay Loam	
3-2	0-4"	Sandy Loam	Very Compact. 10% Gravel. Soil was too compact to get a profile.
3-3	0-7"	Sandy Clay Loam	Compacted
3-3	7"-19"	Sandy Clay Loam	1% Mottles 7.5YR 6/8
3-3	19"-23"	Sandy Clay Loam	Not Compacted. 5% Gravel
3-3	Gravel @ 23"		
3-4	0-12"	Silty Clay	Mottles 15% Compacted
3-4	12"-16"	Clay	Compact Mixed Mottles and Depletions
3-4	16”+ Gravel		
3-5	0”-4"	Clay Loam	
3-5	4"-15"	Clay Loam	
3-5	15"-19"	Silty Clay	3% Gravel
3-5	19"-28"	Sandy Loam	Clay Inclusions (see above) for Redox Gravel
3-6	0”-7"	Silty Clay	
3-6	7"-13"	Clay	Compact Mixed Mottles and Depletions
3-6	13"-22"	Sandy Clay Loam	10% 2.5YR 4/8
3-7	0-7"	Sandy Clay Loam	Roots/Compacted
3-7	7"-12"	Silty Clay Loam	Compact
3-7	12"-14"		Field Rock
3-7	14"-22"	Sandy Clay Loam	7% 2.5YR 4/8. 30% Gravel. Native Soil

APPENDIX C
SWALE INFILTRATION MEASUREMENTS

Table C.1 MPD measurements at I-94 Weigh Station

ID	K_{sat} (in/hr)	ID	K_{sat} (in/hr)	ID	K_{sat} (in/hr)
1CL	30.46	G	7.09	I1	1.62
2CL	9.36	H	7.09	I2	39.63
3CL	0.46	I	1.55	I3	1.89
4CL	12.17	J	25.10	I4	3.20
5CL	0.11	K	11.80	I5	8.88
6CL	17.81	L	13.39	M1	21.66
7CL	6.48	M	1.92	M2	2.20
8CL	3.14	N	6.44	M3	8.26
9CL	2.52	O	9.19	M4	6.91
10CL	14.13	4A	41.04	5CL offset	0.03
11CL	1.16	4B	8.70	12CL offset	0.13
12CL	0.38	4C	28.58	A offset	1.34
13CL	7.58	4D	21.69	B offset	0.01
14CL	3.08	10A	18.11	C offset	0.02
15CL	1.54	10B	24.21	D offset	8.74
A	9.20	10D	11.09	E offset	3.41
B	1.89	10E	4.58	F offset	9.40
C	0.66	D1	44.89	G offset	5.00
D	7.08	D2	9.04	H offset	1.26
E	3.24	D3	2.07	I offset	1.12
F	11.46	D4	17.19		

Table C.2 Double Ring Infiltrometer measurements at I-94 Weigh Station

ID	Infiltration Rate (in/hr)
2CL	0.71
5CL	4.65
6CL	1.03
9CL	0.02
12CL	1.66
15CL	0.13
C	5.06
H	0.85
L	2.22
N	2.01

Table C.3 Turf-Tec measurements at I-94 Weigh Station

ID	Infiltration Rate (in/hr)
2CL	0.50
2CL offset 1	7.00
2 CL offset 2	4.50
5CL	0.25
6CL	0.25
6 CL offset	6.50
9CL	0.25
9CL offset	0.25
12CL	3.25
15CL	5.75
15 CL offset	56.25
C	2.75
C offset	1.00
H	6.50
H offset	8.00
L	11.75
L offset	11.00
N	7.75
N offset	2.75
10D	27.00

Table C.4 MPD measurements at TH-8

ID	K_{sat} (in/hr)	ID	K_{sat} (in/hr)
1	0.29	12e	1.22
2	5.74	13	3.34
3	5.62	14	7.98
4	1.15	15	4.59
5	19.34	16	22.39
6	19.05	17b	14.00
7	7.55	17a	93.51
8c	4.40	17c	3.67
8a	37.11	17d	19.13
8b	12.09	18	6.47
8d	25.37	19	0.03
8e	100.64	20d	14.49
9	23.57	20a	86.09
10	1.47	20b	36.71
11	12.58	20c	40.31
12c	3.06	20e	29.72
12a	106.98	20f	25.78
12b	1.02	21	5.83
12d	6.41		

Table C.5 Double Ring Infiltrometer measurements at TH-8

ID	Infiltration Rate (in/hr)
4	0.48
7	4.89
10	3.22
13	1.65
16	0.98
19	0.09

Table C.6 Turf-Tec infiltration measurement at TH-8

ID	Infiltration Rate (in/hr)
2	7.50
3	0.25
4	1.50
5	7.00
6	4.00
7	9.63
8c	8.75
9	1.50
10	18.00
11	5.25
12c	1.75
13	1.63
14	0.25
15	0.13
16	4.75
17b	0.75
18	1.75
19	2.25
20d	3.50

Table C.7 MPD measurements at TH-212

ID	K_{sat} (in/hr)	ID	K_{sat} (in/hr)	ID	K_{sat} (in/hr)
1	0.06	14	0.01	25	0.57
2	0.06	15	0.26	26	0.74
3	2.26	16center	8.89	27	4.17
4	0.01	16d	0.37	28	2.78
5	2.46	16c	4.80	29	12.61
6	0.00	16b	0.69	30	0.36
7	0.10	16a	8.81	31	3.78
8center	9.56	17	1.59	32	0.63
8f	1.72	18	0.05	33	16.24
8e	1.10	19	0.06		
8d	7.00	20	9.08		
8c	18.73	21	2.18		
8b	28.18	22	2.45		
8a	0.77	23c	80.46		
9	0.24	23a	0.02		
10	10.53	23b	50.69		
11	0.46	23d	20.78		
12	0.18	23e	25.76		
13	0.13	24	0.63		

Table C.8 Double Ring Infiltrometer measurements at TH-212

ID	Infiltration Rate (in/hr)
5	0.01
9	1.16
13	0.19
17	0.15
21	1.91
25	0.79
29	34.87

Table C.9 Turf-Tec measurements at TH-212

ID	Infiltration Rate (in/hr)
1	13.25
2	3.75
4	1.25
5	0.16
6	1.25
8center	0.50
9	0.37
11	19.50
13	33.75
15	6.75
17	14.25
19	3.00
21	0.63
23c	16.50
25	3.37
27	24.00
29	1.13
30	10.13
32	3.75
33	58.75

APPENDIX D

FIELD MANUAL

FIELD MANUAL

FOR

MEASURING INFILTRATION CAPACITY AT PROPOSED OR EXISTING STORMWATER INFILTRATION FACILITIES

Introduction

The purpose of this Field Manual is to give those who will be performing infiltration capacity tests a reference document to guide them throughout the testing process while on site. It is intended to be used in conjunction with the full Protocol, which is a separate document. Most information in this Manual is contained in the Protocol, sometimes in more detail. The information presented here is for quick reference and easy accessibility in the field.

The Protocol gives background information, descriptions, and theory regarding potential measuring devices, determination of the number of tests required, test locations, and other related topics. This Field Manual assumes that the Protocol has already been consulted and a detailed plan for a site visit has already been developed. That plan should include device selection, number of tests to be performed, the location of each test, water volume requirements, the source of water to be accessed, and other details. In other words, this Manual assumes that all planning has been completed and the only thing that needs to be done is to visit the site and perform the tests.

Departure for the Site

Before leaving for the site, be sure to complete the checklist below. Each item in the checklist can either receive a check mark for “Ready” or “N/A.” Each item should receive a check mark in one of the two boxes to confirm that it is either ready to go or that it is not necessary.

____ **Measuring devices**
(insert number in blank)
☐ Ready
☐ N/A

Map of test locations
☐ Ready
☐ N/A

____ **Test location markers**
(insert number in blank)
☐ Ready
☐ N/A

Stopwatch(es)
☐ Ready
☐ N/A

Shovel(s)
☐ Ready
☐ N/A

Drinking water
☐ Ready
☐ N/A

Insect repellent
☐ Ready
☐ N/A

Water supply
(___ gal or liters)
☐ Ready
☐ N/A

GPS coordinates of
Each test location
☐ Ready
☐ N/A

____ **Data/logbook(s)**
(insert number in blank)
☐ Ready
☐ N/A

Camera
☐ Ready
☐ N/A

Hand trowel(s)
☐ Ready
☐ N/A

____ **Soil containers**
(insert number in blank)
☐ Ready
☐ N/A

Soil moisture meter
☐ Ready
☐ N/A

____ **Water containers**
(insert number in blank)
☐ Ready
☐ N/A

GPS device
☐ Ready
☐ N/A

____ **Data loggers**
(insert number in blank)
☐ Ready
☐ N/A

Rubber mallet(s)
☐ Ready
☐ N/A

Sunscreen
☐ Ready
☐ N/A

Copy of user’s manual
☐ Ready
☐ N/A

Wood driving blocks
☐ Ready
☐ N/A

Clipboard(s)

☐ Ready
☐ N/A

Ear protection

☐ Ready
☐ N/A

____
(other item)
☐ Ready
☐ N/A

____
(other item)
☐ Ready
☐ N/A

Safety vest(s)
(other item)
☐ Ready
☐ N/A

Vegetation shears

☐ Ready
☐ N/A

____
(other item)
☐ Ready
☐ N/A

____
(other item)
☐ Ready
☐ N/A

Eye protection
(other item)
☐ Ready
☐ N/A

____
(other item)
☐ Ready
☐ N/A

____
(other item)
☐ Ready
☐ N/A

____
(other item)
☐ Ready
☐ N/A

Notes:

At the Site – Simultaneous Testing

This section is for plans that involve simultaneous testing.

Once at the site, complete the following tasks, as necessary, to collect needed data.

Task 1: Mark each test location with an identifying marker.

Task 2: Dig bore holes at test locations or excavate so tests are performed at proper elevation, if necessary.

Task 3: Transport device, appropriate water volume, and any accessories to the test locations. Transport these materials to the number of locations that will be tested simultaneously.

Task 4: Set up the device at the first test location according to the user's manual and any relevant ASTM standards. Any deviations from planned site activities should be logged in data books. If required, soil samples must be collected and logged and the depth of bore holes, if used, also must be logged. Finally, detailed logs need to be made of the infiltration tests.

Task 5: Start the test at the first location. Record necessary data and/or begin data logging.

Task 6: Begin tests at subsequent locations by repeating Tasks 4 and 5 at each location.

Task 7: Upon completion of a test at one location, confirm complete and correct data collation. Check to make sure that collected data appears reasonable and all expected data has been recorded. If anything appears amiss, repeat the test.

Task 8: Using the equipment and accessories from locations with completed tests, begin testing at additional locations as desired or possible.

Task 9: Complete Tasks 7 and 8 until all locations have been tested.

Task 10: Confirm all test locations have been tested and data appears to be complete and correct. Repeat tests at locations where data does not appear complete and correct.

Upon completion of the above tasks, proceed to the Site Visit Wrap-Up section of this manual.

At the Site – Non-Simultaneous Testing

This section is for plans that involve non-simultaneous (i.e., asynchronous) testing.

Once at the site, complete the following tasks, as necessary, to collect needed data.

Task 1: Mark each test location with an identifying marker.

Task 2: Dig bore holes at the first test location or excavate so the test will be performed at the proper elevation, if necessary.

Task 3: Transport device, appropriate water volume, and any accessories to the test location.

Task 4: Set up the device at the test location according to the user's manual and any relevant ASTM standards. Any deviations from planned site activities should be logged in data books. If required, soil samples must be collected and logged and the depth of bore holes, if used, also must be logged. Finally, detailed logs need to be made of the infiltration tests.

Task 5: Start the test at the location. Record necessary data and/or begin data logging.

Task 6: Upon completion of a test at the location, confirm complete and correct data collation. Check to make sure that collected data appears reasonable and all expected data has been recorded. If anything appears amiss, repeat the test.

Task 7: Transport device and all accessories to the next test location.

Task 8: Transport necessary water volume to the next test location.

Task 9: Complete Tasks 4, 5, and 6 at all locations.

Task 10: Confirm all test locations have been tested and data appears to be complete and correct. Repeat tests at locations where data does not appear complete and correct.

Upon completion of the above tasks, proceed to the Site Visit Wrap-Up section of this manual.

Site Visit Wrap-Up

Finishing the site visit is relatively simple. The following tasks should be completed:

Task A: Replace any soil removed in preparation for the tests. This includes soil removed from any well holes for use of permeameters and any soil excavated for use of infiltrometers. The site must be left so that it is safe for people and animals, even if none are expected on the site. The site must be left in the condition it was in before arriving on site.

Task B: Collect and clean all devices, data loggers, equipment, data books, tools and any other items transported to the site and pack them for return transport.

Task C: If water was gathered onsite from a faucet, fire hydrant, or other similar sources, the water supply must be turned off and returned to its original condition.

Task D: Leave the site.

This concludes activities performed at the site. For data analysis or other details, consult the corresponding user manual for your devices, corresponding ASTM standards (if any), and/or the Protocol document associated with this Field Manual.