Appendix B

Infiltration Estimation Method Selection and Interpretation Guide

Appendix B

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1 Introduction

1.1 Purpose and Intended Use

The characterization of infiltration rates using field testing methods is a critical step in evaluating the feasibility of implementing infiltration BMPs. Screening-level estimates of infiltration capacity are necessary to support BMP placement and selection decisions. If BMPs are selected that rely on a certain infiltration rate, then reliable design-level estimates of infiltration rates are critical to confirm the selected BMP type and support design. The objective of this appendix is to synthesize guidance on infiltration testing to provide the following:

1. A framework for selecting an infiltration testing method based on testing objectives, site conditions, and project phase.
2. Comparison of infiltration testing methods and guidance on appropriate use.
3. Description of critical considerations for interpreting test results and selecting a factor of safety.

The intent of this Guide is to support the overall framework for infiltration decision making and design described in this Guidance Manual. Specifically, this Guide is intended to improve user understanding about available infiltration rate testing methods, appropriate use, and expected accuracy to support selection of the most appropriate approach(es) for a given application.

The intended audience for this Guide includes project managers, stormwater engineers, and planners responsible for scoping appropriate infiltration estimation efforts and interpreting results. This document is not intended to be an exhaustive list of methods nor to provide detailed step-by-step test procedures. References are provided within the text to guide the user to additional test information. Local guidance, criteria documents, and qualified geotechnical/hydrogeologic professionals are expected to serve an important role in selecting and applying testing methods.

1.2 Technical Basis

The recommendations and descriptions presented in this document are based on review of literature studies, state and municipal guidance documents, interviews with practitioners and manufacturers on infiltration testing methods, and interpretation of groundwater mounding analyses presented in Appendix C.

1.3 Orientation to Infiltration Terminology

Various terminology is used in the context of stormwater infiltration. While terms such as permeability, infiltration rate, and percolation are interchanged in colloquial discussion, the differences between terms can be important for selecting and interpreting infiltration testing methods. Key terms include:

- **Saturated hydraulic conductivity** or **Permeability:** Saturated hydraulic conductivity (K_{sat}), also referred to as permeability, is an in-situ soil property that describes the bulk velocity of flow through a soil at a unit hydraulic gradient (Darcy, 1856). Units are expressed in terms of velocity (i.e., in/hr or cm/sec). Saturated hydraulic conductivity is a function of inherent properties of the soil (e.g., grain size distribution), but is also a function of conditional properties of the soil such as density, structure, and compaction of the soil and the viscosity of water (which is function of temperature). In other words, a given soil type does not have an inherent saturated hydraulic conductivity. Variations on hydraulic conductivity include:

- *Horizontal and vertical permeability.* Saturated hydraulic conductivity through soils is often different in the horizontal and vertical dimensions. This is known as "anisotropy" and is a function of various factors including particle arrangement and soil layering.
- *Unsaturated hydraulic conductivity.* Unsaturated hydraulic conductivity is generally less than saturated hydraulic conductivity.

- **Infiltration Rate:** Infiltration rate is the rate of flux of water into a given soil structure under a given set of surface and subsurface conditions. Similar to saturated hydraulic conductivity, infiltration rate can be influenced by soil properties, layering of soil, density, and compaction. However, infiltration rate can also be influenced by the suction forces associated with soil wetting, the soil moisture conditions of near-surface soils, the hydraulic gradient on the soil, and groundwater mounding processes. Factors affecting infiltration rate include the limiting rates of the surficial soils as well as the "capacity" of the "infiltration receptor" to accept infiltrated water over an extended period. The "infiltration receptor" refers to the combined system of the unsaturated zone and local groundwater that receives the infiltrated stormwater. Long term infiltration rates are a function of how fact soil can enter the soil, but also how much water can be received by the infiltration receptor over time.

  Infiltration tends to exceed saturated hydraulic conductivity during soil wetting, then declines and approach the saturated hydraulic conductivity. If a groundwater mound forms that interacts with the hydraulic gradient below the BMP, this can further reduce the infiltration rate. Variations on infiltration rate include:

  - *Measured infiltration rate***.** This refers the rate of flux of water into the soil measured as part of an infiltration test. This may not reflect actual infiltration rate under operating conditions.
  - *Design infiltration rate.* This is an infiltration rate estimate used in the design of a stormwater infiltration system. It may include adjustment to account for factors not reflected in the measured infiltration rate, such as the capacity of the infiltration receptor, the geometry of the BMP, siltation/clogging, and general uncertainty.
  - *Full-scale infiltration rate*. This is the actual rate of infiltration of water below a BMP at full scale. This is not a fixed number. Actual infiltration rate is expected to vary seasonally with temperature, over time (with clogging, compaction, weathering and plant processes), or periodically (as a function of groundwater mounding).

- **Percolation:** Percolation refers to the flux of water in the soil subsurface. It is analogous to infiltration rate, but applicable to movement of water within the soil rather than the movement of water into the surface of the soil. Like infiltration rate, it is dependent on inherent soil properties as well as in-situ attributes such as layering of soil, density, compaction, degree of saturation, temperature, and groundwater mounding. Some infiltration rate estimation methods rely on measurements of percolation rate. These can be reasonably translated to an estimated infiltration rate where subsurface soils are not distinctly different than near-surface soils and where the test has proceeded for a long enough period to assess saturated percolation processes.

1.4 Unifying Themes for Selection, Application, and Interpretation of Infiltration Estimation Methods

This section summarizes the critical conceptual underpinnings of this Guide.

- **Direct testing of in-situ soils is almost always needed to obtain a reliable estimate of design infiltration rate.** Soil infiltration rate can vary greatly (an order of magnitude or more) with minor variations in particle size distribution, particle arrangement, density/compaction, and other factors. None of these factors can be reliably considered via mapping of soil texture classes or laboratory soil analyses. When a reliable infiltration rate must be obtained, this mandates that a direct test of in-situ soil infiltration properties be conducted.
- **Each testing method yields different information.** For example, a borehole test typically measures the rate of saturated percolation, mostly in the lateral direction, from a circular hole. A ring infiltrometer measures the rate of water flux into the soil when water is ponded onto the soil surface. These tests measure different parts of the soil column and in different directions. Other tests measure other attributes of the soil. This Guide attempts to explain what specific property of the soil is being measured in each method.
- **Tests are more reliable when they require less translation to the type of BMP proposed.** Translation approaches are needed to account for differences in dimensionality and infiltration processes between the test and the proposed BMPs. When the type of BMP is known, tests should be selected that best approximate the infiltration processes that will occur from the BMP to reduce the need for translations and corrections. For example, trenches and narrow basins have more infiltration into their side walls while broad flat BMPs rely primarily on vertical infiltration.
- **Soil conditions can also influence the reliability of tests.** When soils are highly uniform vertically, there is less potential for error. However, when soils are layered, the conversion from horizontal flow measurements to estimates of vertical flux through soils can be highly uncertain.
- **Even the best infiltration test is still limited.** By their nature, testing methods involve smaller areas and less volume of water than the full-scale facilities they are intended to approximate. As such, testing methods inherently do not account for factors such as soil variability and groundwater mounding.
- **Other information can complement the interpretation of infiltration tests.** For example, borelogs provide valuable information about soil layering, confining layers, and/or groundwater. Slug testing data, when available, can help to validate any soil infiltration test results. Overall, supplemental information can be used to better predict how the measured information from a test would be expected to translate to full-scale infiltration rates.
- **A reliable estimate of design infiltration rate is not always needed.** Obtaining a reliable estimate of infiltration rate can be costly and time-consuming. As explained in the main body of this Guidance Manual, a reliable estimate of design infiltration rate is not always needed. BMPs can be designed to allow for maximized partial infiltration while providing a pathway for treated water if infiltration capacity is exceeded.

1.5 Organization

This guidance document is organized sequentially to guide the user through the method selection and interpretation process within the following three sections:

Section 2: Introduction to Methods provides a summary of infiltration estimation methods. Fact Sheets provided in Appendix B provide additional details.

Section 3: Guidance for Method Selection provides an overview of included methods, critical selection considerations, and selection procedures/flow charts based on project phase.

Section 4: Guidance for Method Interpretation describes critical considerations for interpretation of infiltration test results including test geometry, compaction, temperature, groundwater mounding, and selection of an appropriate factor of safety.

2 Introduction to Common Methods

2.1 Categories of Infiltration Rate Estimation Methods

Five different categories of infiltration rate estimation methods are considered in this Guide:

1. **Regional Maps:** NRCS Soil Surveys or local data collection efforts can provide information on general soil properties and distributions within a project site. These may include ratings of infiltration or drainage capacity, such as the hydrologic soil groups (HSG). NRCS soil survey data typically extend only from the surface to a depth of approximately five feet or to bedrock, whichever is shallower, so soil survey data are only reflective of surface soils.
2. **Correlation Methods:** These methods involve development and application of correlations that have been developed between hydraulic conductivity and various other soil properties, such as soil grain-size, cone penetrometer test (CPT) readings, or other rapid screening methods. These correlations allow data obtained from other site investigation activities (borings, soil analyses, CPT) to be used to estimate saturated hydraulic conductivity.
3. **Open Pits:** These methods involve excavating a pit near the surface and filling it with water; the rate of water flow into the bottom and walls of the pit is used to estimate the infiltration rate.
4. **Infiltrometers:** These methods typically involve a cylindrical apparatus placed at the soil surface and filled with water. The measured infiltration rate out of the bottom of the infiltrometer into the soil is used to estimate the infiltration rate of the soil.
5. **Boreholes Methods:** These methods involve drilling a borehole, introducing water into the boreholes and measuring the rate at which water moves into the walls and/or floor of the borehole floor.

In the case of open pits, infiltrometers, and borehole methods, procedures for operating the test can vary. Two key options include falling-head procedures or constant head procedures. A falling head procedure involves monitoring the rate of fall of water into the system. A constant head procedure involves introducing water at a rate necessary to maintain a constant head, while measuring the rate of water addition.

Table 1 summarizes these categories of testing or estimation methods relative to key distinguishing criteria.

Table 1. Comparison of assessed infiltration method types based on scale, dimensionality, and elevation factors

Method Type	Included Testing or Estimation Methods	Scale of Test	Directionality	Elevation
Regional Maps	Soil Maps	Landscape scale Estimate (no test)	Note considered.	Surface and subsurface strata mapped (≈10-20 feet of surface)
Correlation Methods	Grain Size Analysis Cone Penetrometer	Point measurements from other investigations	Not considered.	Sample or measure any strata
Open Pit Methods	Simple Open Pit Small-scale Pilot Infiltration Test (PIT) Large-scale PIT	Small to large point measurement dependent on pit size (pit areas: 2 to 100 ft^2)	Mix of vertical and lateral, depending on the size and shape of the pit	Near surface only
Infiltrometer Methods	Single Ring Double Ring Dual Head Modified Philip-Dunne Mini Disk	Small to medium point measurement (infiltrometer diameters: 0.2 to 4 ft)	Primarily vertical, depending on method	Near surface only
Borehole Permeameter Methods	Constant Head Well Permeameter Aardvark Permeameter Guelph Permeameter	Point measurement (borehole diameters: 0.1 to 1 ft)	Primarily horizontal depending on method and implementation	Shallow subsurface to deep strata

2.2 Regional Soil Maps

NRCS Soil Surveys and geological maps can provide useful information for quickly evaluating infiltration potential on a broad geographic context. Soil survey data typically characterize only soil within five feet of the ground surface or to the depth of bedrock, whichever is shallower, so this data only provides a characterization of surface soils. Guidance manuals and studies generally recommend that these types of datasets be used with care and confirmed with on-site measurements when feasible (FHWA, 2009). Confirming mapped data with available site data such as soil borings, observed soil textures, and biological indicators (e.g., wetland plants) can provide an inexpensive means of improving the reliability of regional maps. For example, if the maps report Hydrologic Soil Group D (lowest infiltration capacity) uniformly across the site, and the results of borings show consistent presence of silt or clay soils, then this is generally a reliable basis for rejecting full infiltration BMPs and pursuing alternative BMP types. However, Caltrans (2003) observed that the use of HSG D classification as the sole metric to exclude study locations resulted in ruling out locations that may have been feasible had testing been conducted. Regional soil maps are generally only appropriate for preliminary screening phase investigations.

2.3 Correlation Methods

Correlation measurements utilize empirical equations to relate soil physical properties to hydraulic conductivity estimates. These tests may provide an inexpensive method for testing large areas. Correlation methods are generally only considered appropriate for preliminary feasibility screening phase assessments due to the residual error common in the correlations that underlie these methods. Confidence can be improved if the data used to develop correlations is specific to the conditions and geologic units that are under investigation.

1. **Grain Size Analysis:** This method uses empirical formulas to indirectly estimate hydraulic conductivity based on soil grain size distribution (example: Philips and Kitch, 2011). Grain size analysis may be inaccurate when soils are compacted or contain a large percentage of fines (Hinman, 2009; Philips and Kitch, 2011). Grain size correlation methods are more appropriate when relationships are developed using local soil conditions (example: WSDOE, 2012 – Massmann Method).

   Methodology Reference: WSDOE (2012)

2. **Cone Penetrometer Testing:** A cone penetrometer test involves advancing a small probe into the soil and measuring the relative resistance encountered as the probe advances. This is mostly commonly done to evaluate soil strength and layering. Correlation methods can be developed that relate resistance measurements to hydraulic conductivity (Lunne et al. 1997). Philips and Kitch (2011) found this method to be highly variable compared to direct measurement. Additional field experience with these methods has not been identified. In general, this method could be considered as one line of evidence. The use of a truck-mounted push sampler could have similar applicability and limitations.

   Methodology Reference: Lunne et al. (1997)

2.4 Open Pit Tests

Open pit tests involve excavation of a hole near the ground surface and measurement of the rate of water addition at a maintained water level (constant head test) or the rate of water level recession (falling head test). Open pit tests are applicable for surface infiltration testing with the bottom of the hole set approximately at the depth of the proposed infiltrating surface of the BMP. The dimensionality of open pit tests may result in a moderate overestimate of BMP infiltration rates due to water moving laterally through the pit side walls; a correction factor should be applied. The primary difference among individual infiltration tests is the size of the pit and the rigor of execution. Large pits generally provide more reliable results, but also require additional excavation and water.

1. **Simple Open Pit:** The Simple Open Pit Test is a falling head test in which a hole at least two feet in diameter is filled to a level of 6” above the bottom and the rate of water level fall is measured. The key limitations of this test are that it measures a relatively small area, does not require pre-soaking, does not necessarily result in a precise measurement, and may not be uniformly implemented by different practitioners. However, it is considered a reliable screening test and can be efficiently performed across a site.

   Methodology Reference: Fact Sheet B.1 & City of Portland (2016) Section 2.3.6

2. **Small Scale Pilot Infiltration Test (PIT):** To perform this test, a hole is excavated with a footprint of at least 12 sq-ft to a depth of at least 12 inches. This test is similar to the Simple Open Pit Test, but covers a larger footprint, includes a pre-soak stage, and involves a more specific testing procedure. Nonetheless, it remains a relatively simple test. This test has the advantage of measuring infiltration over a larger area and better resembles the dimensionality of a typical small-scale BMP. Because it includes both vertical and lateral infiltration, a vertical correction should be applied for larger scale BMPs. Multipliers are discussed in Section 4.2.

Methodology Reference: Fact Sheet B.2 & WADOE (2013). Note: multiple variations on this this type of procedure exist.

3. **Pilot Infiltration Test (PIT):** This test is a constant head test and is closer in scale to a full-scale infiltration facility. The required areas have been developed by WSDOE specifically for stormwater applications (WSDOE, 2012). This test has the advantage of being more resistant to bias from localized soil variability and closely resembling the dimensionality of a full scale BMPs. However, this method requires a large excavation area (100 sq-ft) and a commensurately large water supply. This method is most applicable for large infiltration facilities where a high degree of certainty is required.

   Methodology Reference: WSDOE (2012) Section 3.3

Table 2 provides a summary of practical differences between pit-type infiltration tests.

Table 2. Comparison of Open Pit Testing Methods

Method	Testing Time[1]	Water Volume[2]	Difficulty	Soil Type Compatibility	Testing Depth	Approximate Supply Costs
Simple Open Pit Test	2 to 4 hours	100 to 250 gal	Simple, little to no training required.	All soil types.	12 inches	Limited
Small Scale PIT	10 to 14 hours	350 to 1,000 gal	Medium, training and flow metering equipment required.	All soil types.	12 inches	Water truck, backhoe, and flow meter
Large Scale Pit	12 to 16 hours	3,000 to 8,000 gal	Medium/High, training and flow metering equipment required. Supplying enough water can be challenging.	All soil types but supplying enough water to generate ponding can be infeasible if soils are very permeable.	12 inches	Large water truck or hydrant source, backhoe, and flow meter

1- Includes preparation and pre-soak periods; multiple tests could be done in parallel.

2- Depends on soil infiltration rate. The estimated range is based on 0.25 to 10 inch/hour soil infiltration rates.

2.5 Infiltrometer Tests

Infiltrometer methods generally provide standardized testing methods for surface infiltration rates. Due to the small point measurements of some tests, multiple tests may be needed to account for spatial variation. It is generally recommended that an adjacent soil boring be conducted to assess ground water and confining layer conditions.

1. **Single Ring:** This test is a constant head test using a single cylindrical ring driven into the surface of the soil. This test is relatively simple to conduct and has more standardized geometry than open pit methods. However, it is still a relatively small-scale test and can only be conducted near the existing ground surface. Driving the ring into the ground limits lateral infiltration; however, some lateral infiltration is generally considered to occur as a bulb forms below the test. There are numerous procedures. Smaller rings and shallower embedment depths generally require greater correction for unsaturated, three-dimensional soil dynamics. Larger tests are costlier, but do not require corrections.

   Methodology Reference: Many variations exist. Example references:

Large Single Ring – Fact Sheet B.3 & Riverside County (2011) Appendix A

Small Single ring with Conversion Equations: Hatt and Le Coustumer (2008)

2. **Double Ring:** The Double Ring Infiltrometer is a constant head test using an apparatus with two concentric rings. The annulus between the two rings is intended to saturate the soil outside of the inner ring such that infiltration from the inner ring is restricted primarily to the vertical direction. This test is generally considered to provide a direct estimate of vertical infiltration rate for the specific point tested and is highly replicable. However, given the small diameter of the inner ring (standard diameter = 12 inches), this test only measures infiltration rate in a small area. The added effort and cost of isolating vertical infiltration rate may not be warranted considering that BMPs typically have a lateral component of infiltration as well. Therefore, while this method has the advantages of being technically rigorous and well standardized, it may not be the most representative test for estimating full-scale infiltration rates.

   Methodology Reference: Fact Sheet B.4 & ASTM International (2009)

3. **Dual Head:** The Dual Head Infiltrometer is a propriety device manufactured by Decagon Devices which utilizes automated, multiple stage infiltration measurements to evaluate and correct for three-dimensional, unsaturated soil infiltration processes. Hydraulic conductivity is calculated based on corrections for measured soil absorptivity and capillary length. The small (6-inch) infiltrometer diameter results in a specific point measurement; however, it requires relatively minimal water volume compared to larger single-ring and double-ring infiltrometers. After inserting the ring and filling the water reservoir, execution and interpretation of the test is fully automated.

   Methodology Reference: Fact Sheet B.5

4. **Modified Phillip Dunne (MPD):** The MPD is a small diameter (2-inch) proprietary infiltrometer system designed specifically for measuring stormwater BMP surface infiltration rates (Nestingen, 2007) and sold by Upstream Technologies. This test is similar in geometry to a small-diameter single ring infiltrometer but uses a falling head method. It differs in the calculations used to account for three-dimensional unsaturated flow processes below the system. In addition to continuous measurements of the rate, the system also measures soil moisture and includes this measurement to calculate the saturated hydraulic conductivity of the soil.

   Methodology Reference: Fact Sheet B.6 & Ahmed et al. (2011) Appendix C

5. **Mini Disk:** The mini disk infiltrometer is a proprietary device intended to provide rapid estimates of surface infiltration rates. It is the smallest infiltrometer currently available (1.2-inch diameter). The test measures unsaturated hydraulic conductivity. The mini disk test requires multiple tests to account for spatial variation. The test requires a very smooth and uniform surface.

   Methodology Reference: Fact Sheet B.7

Table 3 provides a comparison of key attributes of infiltrometer test methods.

Table 3. Comparison of Infiltrometer Testing Methods

Method	Dia. of Ring	Testing Time	Water Volume	Difficulty to Execute	Post-Processing Needed?	Soil Type Compatibility	Approx. Supply Costs
Small Single Ring	4 inches	2 to 3 hours	5 to 10 gal	Simple, little to no training required.	Conversion equations required	All soil types.	$100
Large Single Ring	24 inches	8 to 12 hours	100 to 1,000 gal	Moderately difficult to set up and maintain constant head	No. Use rate of infiltration directly.	All soil types	$1,000
Double Ring	12 inches (inner ring)	8 to 12 hours	100 to 1,000 gal	Moderately difficult to set up and maintain constant head.	No. Use rate of infiltration directly.	All soil types.	$2,500
Dual Head	6 inches	1.5 to 3 hours	5 gallons to 10 gal	Simple/Medium, some training or practice runs ideal.	Calculations done by device software.	Majority of soils, not ideal for large soil pores.	$3,500
Modified Phillip Dunne	4 inches	1 to 2 hours	6 gal	Simple, little to no training required.	Calculations done by device software.	Unsuitable for rocky soils.	$5,000
Mini Disk	1.2 inches	0.5 to 5 hours	1 gal	Simple, little to no training required.	Calculations done by device software.	Soils must be uniform and smooth at the surface.	$300

2.6 Borehole Permeameter Tests

Borehole tests may be the only viable alternative when infiltration rate testing is required below the ground surface. The primary limitation in using borehole tests is that the direction of infiltration is primarily lateral, which may be challenging to translate to vertical infiltration that occurs below most BMP types. This can be an inherently-limiting factor for the use of borehole permeameters, particularly where soil layers vary in properties, results in greater lateral permeability than vertical permeability. This limitation can be partly offset by first determining the limiting soil layer and then conducting borehole tests over a narrow depth interval to isolate the limiting layer. Borehole methods may require a well permit from the local well permitting agency depending on depth of well and the duration of the test.

1. **Constant Head Well Permeameter (aka Borehole Permeameter):** The constant head well permeameter (CHWP) method involves excavation of a borehole, maintaining a constant head in the borehole and measurement of the rate of water needed to maintain a constant head. Test wells are typically 6 to 8 inches. The well is drilled to the depth of interest. The depth of water maintained in the hole can be selected to approximate the zone of interest. The flow rate needed to maintain a constant head is converted to an estimate of the bulk hydraulic conductivity of the soil using several potential equations. Measured infiltration is primarily in the horizontal direction. To convert the constant head flowrate to an estimated saturated hydraulic conductivity, the assumption must be made that soils are uniform and do not have different horizontal properties than vertical properties. Logging of soil cores is necessary to evaluate this assumption and determine the extent to which this may be

violated. Where there are higher permeability lenses among lower permeability soils, this method could greatly overestimate the vertical hydraulic conductivity of a soil.

Methodology Reference: Fact Sheet B.8 & Kindred (2017). Note, borehole percolation tests can also be conducted with falling head. However, the interpretation of falling head tests requires different and more complex equations to account for change in head over the monitored interval.

2. **Aardvark Permeameter:** The Aardvark Permeameter is a type of proprietary well permeameter. The test is conducted in a 4-inch hole. The apparatus includes a water level regulator that extends into the hole to maintain a constant head in the hole. This method supports relatively narrow testing intervals at extended depths. The test typically induces approximately 6 inches of constant head ponding in the bottom of the hole. This can help reduce some of the limitations of a CHWP method as soil properties tend to be more uniform within narrower depth intervals. The Aardvark Permeameter system is sold with a digital scale connected to a computer to allow automated measurement and data interpretation. The scale measures the water tank as it empties. The equations for estimating saturated hydraulic conductivity are implicit in the software program.

   Methodology Reference: Fact Sheet B.9

3. **Guelph Permeameter:** The Guelph Permeameter is a proprietary well permeameter. It is generally similar to the Aardvark Permeameter, but conducted in a 2.4-inch hole, and water level is maintained by an in-hole Mariotte bottle device that only supports depths up to approximately 5 feet. This method has the advantage of shorter testing times and smaller required water volumes. It is also able to isolate narrower testing intervals to limit tests to more uniform soil properties.

   Methodology Reference: Fact Sheet B.10

Borehole testing methods are compared in Table 4.

Table 4. Comparison of Borehole Testing Methods

Method	Bore-hole Dia.	Depth of Test Interval	Testing Time	Water Volume[1]	Difficulty	Post-Processing	Approximate Supply Costs
Constant Head Well Permeameter	Varies. Typ. 6 to 8 inches.	Any depth.	4 to 24 hours	50 to 1,000 gal	Moderate/High. Depends on depth. Requires professional interpretation of data.	Professional judgement/ expertise required to interpret data.	$2,000 for well supplies, transducer, and water source. Excludes drilling rig.
Aardvark Permeameter	4 inches	Up to 50 feet	1 to 2 hours	5 to 10 gallons	Low/Moderate. Training and familiarity with device and procedures required	Vendor-supplied computer software connected to digital scale.	$2,400 device with scale and software $1,800 well preparation kit.
Guelph Permeameter	2.4 inches	Up to 5 feet.	0.5 to 2 hours	1 gallon	Low/Moderate. Training and familiarity with device and procedures required.	Vendor-supplied calculation spreadsheet.	$3,000 to $4,000 for full kit.

1 – Depends on well diameter, height of testing interval and permeability of soil.

3 Guidance for Selection of Infiltration Estimation Methods

The selection of an appropriate testing method is dependent project goals and requirements, the spatial extent of the site to be investigated, site conditions, and practical considerations. This section includes general considerations applicable to all projects and considerations specific to project phase.

3.1 Overall Considerations for Method Selection

The role of infiltration testing differs based on project objectives and site conditions. Some projects may not require any infiltration testing while others will require detailed testing in multiple project phases. Several factors are important to consider sequentially when planning infiltration testing (Figure 1).

Figure 1. General Infiltration Rate Testing Considerations

The following sections identify key questions that can help support selection of an infiltration testing or estimation method. Based on answers to these questions, guidance is provided related to the categories or specific types of tests that may be most appropriate.

3.1.1 Project Goals and Requirements

Defining the objectives and requirements of the project with regards to infiltration rate estimation is a critical first step in defining the extent and timeline of infiltration testing. Additionally, identifying the key go/no-go decision points within the project delivery process is important to determine the appropriate timing and phasing of the investigations.

<u>Example Questions</u>

- *Does the project need to use infiltration to the "maximum extent practical" or to a specified level to comply with applicable requirements?*
- *Does the project need to provide a technical demonstration that infiltration is not feasible?*
- *Do regulatory criteria specify the methods and/or number of tests needed to support findings of infiltration testing?*
- *Would there be other benefits to stormwater infiltration that justify investigating infiltration feasibility if not required by regulations?*
- *When do infiltration decisions need to be made to support project permitting? Is this needed for environmental clearance, or just to support design?*
- *Does available information (e.g., soil maps, boring logs, soil texture classes) suggest that there is infiltration potential for the site?*

These questions are applicable to the first step in the infiltration decision making process described in Chapter 2 of the main Guidance Manual. Through this process, project planners will typically have an initial understanding of the potential feasibility of infiltration at the site. For sites that are possibly feasible, the project team can tailor the investigation scope and methods to identify feasible areas, support design-level assumptions, and/or provide a technical basis for the revising this assumption. For sites that appear likely infeasible, the project team can tailor the investigation scope and methods to provide confirmation of this finding a way that satisfies applicable regulatory standards.

3.1.2 Other Controlling Feasibility Criteria

Other factors may limit infiltration feasibility besides soil infiltration rates, such as groundwater contamination and geotechnical considerations.

Example Questions

- *Have feasibility criteria apart from infiltration rate been investigated and determined to be allowable?*
- *Is infiltration testing necessary to support other feasibility evaluations, such as geotechnical risks or groundwater balance issues?*

If other factors control feasibility, then infiltration testing may not be needed to support BMP selection. In general, project teams should only conduct infiltration testing if other feasibility criteria have been evaluated and cleared.

3.1.3 Project Size and Layout

The size of the project area considered for BMP implementation and the uniformity of soil conditions should influence the selection of testing methods.

Example Questions

- *How constrained is the site with respect to BMP placement?*
- *What types and locations of BMPs appear most feasible for the project?*
- *Is an assessment of the infiltration rate at multiple locations valuable or required to support project goals?*

If the size of the project is small and/or BMP locations are inflexible, then use of a more accurate and intensive approach may be warranted, regardless of project phase. This assumes that available information suggests that infiltration may be feasible in these locations. If not, then simpler, more efficient methods may be appropriate to rule out infiltration in these areas and proceed to an alternative management approach.

However, if there is flexibility to allow the results of site investigation to inform BMP placement, then it may be advantageous to obtain more rapid estimates across a broader area as part of a first phase of investigation, and then focus on selected BMP locations with more intensive testing methods provided investigations show potential feasibility. As introduced in Section 2, investigation methods vary considerably in their time requirements, cost, and complexity.

3.1.4 Soil Conditions & BMP Geometry

Factors relating to the uniformity of soil conditions, geometry of the proposed BMP, and the elevation of the BMP compared to current grades can support selection of an appropriate infiltration test and number of tests needed.

Example Questions

- *How variable are soils at the project location both vertically and laterally?*
- *What types of geologic formations are present on the site? Are the soils colluvial, alluvial, fluvial, lacustrine, etc.?*
- *What is the proposed final grade of the project with respect to the current ground surface?*
- *What type of infiltration test is most representative of the geometry of the proposed BMP?*

Sites with variable soil conditions may require additional tests at the planning level to determine infiltration rates in different soil zones. In sites with large variability, it may be inappropriate to make initial conclusions from soils maps. Rather, an initial round of preliminary screening-level tests (such as with more rapid, less accurate methods) may help characterize the site and provide information for screening and siting of BMPs.

Sites with variability among soil layers (i.e., mix of coarser and finer-grained layers) can be unsuitable for borehole-based testing methods as lateral flow into coarser layers does not represent the rate of vertical flow through finer layers. When a BMP will be located below current grade and soils are layered, this can greatly impair the ability to obtain a reliable estimate. This could be the basis for rejecting the use of full infiltration BMP at that location.

Infiltration tests are most accurate when the geometry of the test is similar to the geometry of the proposed BMP with regards to invert elevation and side wall geometry. Ideally, infiltration tests will be conducted at or slightly below the invert elevation of the BMP.

3.1.5 Practical Considerations

Practical considerations for selection of infiltration estimation methods include budget, equipment availability, sources of water, time requirements, and required expertise/local experience. These factors can be used to compare specific methods once a feasible method type has been determined.

Example Questions:

- *What is the budget available for conducting infiltration testing?*
- *Could other design costs potentially be reduced (i.e., conveyance, flood control) if increased budget were allocated to thoroughly investigating infiltration opportunities?*
- *Which infiltration tests can be conducted with available expertise and equipment?*
- *What experience does the local agency or firm have with a given method?*
- *Is the volume of water needed for a test a limiting factor?*
- *How quickly do tests need to be conducted to support necessary decision making?*

Tests vary greatly with respect to time requirements. The summary tables presented in Section 2 and the Fact Sheets presented in Appendix X.1 can help screen testing methods based on practical factors.

Because all infiltration tests require translation/extrapolation to estimate full scale system performance, the local agency's experience with the reliability of a given method for the local soil formations can be a very important factor in selecting a method.

3.2 Project Phase-Specific Considerations for Method Selection

In general, simpler and more efficient methods of infiltration rate investigation are appropriate for preliminary infiltration feasibility screening and identification of potential BMP sites. At this phase, it may not be necessary to conclusively demonstrate feasibility; rather to provide rapid information to help support early decision making. In some cases, more accurate and time-intensive methods may be necessary to support the design phase. This is particularly true if full infiltration BMPs will be used. Table 2 summarizes the suitability of the five different infiltration testing methods for preliminary feasibility screening and design phase assessments.

Table 5. Guidelines for Use of Methods based on Project Phase

Method Type	Guidelines for Preliminary Feasibility Screening	Guidelines for Design Phase Investigation if Full Infiltration BMPs are Proposed
Regional Maps	• Regional maps can help with rapid screening. • Maps are more reliably if they can be compared to other site-specific data, such as bore logs and physical observations. • For complex sites and higher regulatory burden, maps may not be adequate.	• Not suitable for full infiltration BMPs.
Correlation Methods	• If available and locally-validated, then these methods can be useful.	• Only suitable for full infiltration BMPs if strong local correlations to full-scale systems have been developed (e.g., Washington State Massmann Method) and appropriate factors of safety are included.
Open Pit Methods	• Simple open pit tests (4 sq-ft) are appropriate where proposed BMPs will be near existing grade. • Multiple pit tests can be conducted simultaneously to improve efficiency. • Spacing of 50 to 200 feet is appropriate, depending on soil variability.	• Small-scale PIT (>10 sq-ft) is reliable for developing design infiltration rates for full infiltration BMPs.
Infiltrometer Methods	• Smaller-scale systems such as the small-diameter single ring, Dual Head, MPD, Minidisk are more efficient.	• Any infiltrometer can support design if the necessary conditions for the method are met. • Smaller diameter and lower volume tests may require greater number of tests to compensate for the small volume of soil tested by each method.

Method Type	Guidelines for Preliminary Feasibility Screening	Guidelines for Design Phase Investigation if Full Infiltration BMPs are Proposed
Borehole Methods	• Yes, if below grade installation is anticipated and dimensionality correction is used. • Proprietary methods (e.g., Aardvark and Guelph Permeameters) offer greater efficiency than standard borehole methods.	• Most appropriate for infiltration trenches and drywells. • For other BMP types that rely primarily on vertical infiltration, assess bore logs to determine if soil is uniform with depth. If so, then these tests may be reliable to estimate vertical infiltration rate. A higher factor of safety is still recommended in this case. • Testing at smaller depth intervals within homogeneous soils can allow more reliable translation to vertical infiltration rate. • If soil layers have high variability in properties, then these tests are generally not reliable for estimating vertical infiltration.

3.3 Testing Frequency and Locations for Design-Phase Investigations of Full Infiltration BMPs

Based on previous planning and design efforts, determine the proposed location of each infiltration BMP that requires design phase infiltration testing. The number of required tests is dependent on footprint size and soil variability. Design phase testing should be overseen by a qualified professional. The following guidelines have been synthesized from various local guidance manual. Project- and site-specific judgement should always be applied to determine the scope of design-phase testing.

Minimum Number of Tests: Conduct three infiltration tests for every full infiltration practice. Tests should be conducted within the footprint of the practice or within 20 feet of the perimeter in representative soil formations.

Additional Tests for Large Facilities: For practices with footprints greater than 10,000 ft^2, conduct one additional test for every 10,000 ft^2. In general, no more than five valid tests are necessary for large facilities, unless deemed valuable by a qualified professional assessing the site or the reviewing jurisdiction.

Test Spacing: Tests should be evenly spaced within the practice footprint and at a minimum of one test for every 100 ft. If soil conditions are variable, additional tests may be necessary to characterize different zones.

Infiltration Test Method: Consider the infiltration testing method in determining the number of required tests. A single large-scale pit test may be sufficient to characterize a facility. Small point measurement methods may require additional measurements. Consult method descriptions (Section 2) and the infiltration testing method fact sheets (attached to this Guide) for guidance.

Test Elevation. The elevation of infiltration tests should be near the final facility grade (within approximately 2 feet). If a confining layer will be within 5 feet of the planned facility bottom, infiltration testing should characterize the confining layer.

Accompanying Data. Each infiltration test should be accompanied by a soil boring test to a depth of 15 feet below the planned infiltration bottom to aid in interpretation based on groundwater conditions and soil stratification.

Estimation of Future Cut Locations. If BMPs will be installed more than approximately 5 feet below grade infiltration rates can be estimated using borehole testing methods. The estimated infiltration rate can be reasonably scaled to full scale rates for infiltration trenches. If the BMPs will rely on vertical infiltration (e.g., basins, swales), then borehole tests should be conducted within the most limiting soil layer without the influence of any more permeable layers. Testing of soils after excavation to expose existing grade may also be desirable to confirm findings.

BMPs Constructed in Fill: It is not possible to conduct tests prior to construction that reliably estimate infiltrations rates of future fill. Therefore, if full infiltration BMPs in fill are proposed, testing should be conducted after placement of fill to confirm feasibility. Construction-phase testing may not be feasible, which may eliminate consideration of full infiltration BMPs in areas of proposed fill.

4 Guidance for Interpretation of Test Methods

The objective of this section is to provide guidance on selecting an appropriate design infiltration rate using collected infiltration test results.

4.1 Factors Applicable to All Testing Methods

4.1.1 Compaction

Compaction of soil has a major influence on infiltration rates (Pitt et al. 2008). Intentional compaction is an essential aspect of roadway construction and incidental compaction due to machinery movement, fill placement, material stockpiling and foot traffic may be difficult to avoid. Infiltration testing strategies should attempt to measure soils at a degree of compaction that resembles anticipated post-construction conditions. Ideally, infiltration systems should be located outside of areas where intentional compaction will be required and should be staked off to minimize incidental compaction from vehicles and stockpiling. For these conditions, no adjustment of test results is needed.

In some cases, infiltration BMPs will be constructed in compacted areas. For these areas, it may be appropriate to conduct infiltration tests after applying a representative degree of compaction to the soil. Alternatively, a higher factor of safety could be applied to account for anticipated infiltration after compaction (Section 4.3). To develop a factor of safety associated with incidental compaction, samples could be compacted to various degrees, their hydraulic conductivity measured, and a “response curve” developed to relate the degree of compaction to the hydraulic conductivity of the material. This should ideally be done to in-situ soils rather than remolded laboratory samples. Laboratory remolding influences the structure of the soil.

4.1.2 Precipitation Conditions

The current saturation levels of the soil can influence the observed infiltration rate. To the extent possible, infiltration rate assessments should be conducted for a long enough duration to result in stabilization of test results. However, when possible, conducting infiltration tests during the wet season or during wet periods can improve the reliability of results and may allow tests to stabilize more quickly (i.e., more efficient testing). Precipitation conditions may be assessed using the methodology provided in Table 6 and the corresponding directions below, adapted from WDNR (2017).

When testing infiltration in a borehole or excavation, it may be necessary to discontinue testing during and immediately following precipitation. If rainfall/runoff is entering the hole, this can bias results.

Table 6. Precipitation Conditions Assessment Table

Month		Average Local Monthly Rainfall (in)	30% Chance Rainfall (WETS average, in)		Current Year Rainfall (in)	Condition	Condition Value	Weight Value	Product of Condition and Weight Value
			Less Than	More Than					
Current Month								3	
Previous Month								2	
Two Months Ago								1	
								Sum:	
								Overall Condition:	

Directions:

Refer to WDNR (2017) for a worked example.

1. List the current month and previous two months in the table.
2. Determine the average local monthly rainfall from a greater than 25-year period from NRCS WETS tables or another source.
3. Determine 30th percentile and 70th percentile local average monthly rainfall values from NRCS WETS tables or another source.
4. Determine the current and previous months rainfall sums. If in the middle of a current month, normalize based on days to a monthly total.
5. Determine the monthly rainfall condition and condition values as follows:
   - **Dry:** *Current Year Rainfall* < *30% Less Than*, Condition Value = 1
   - **Normal:** *Current Year Rainfall* is between *30% More Than* and *30% Less Than*, Condition Value = 2
   - **Wet:** *Current Year Rainfall* > *30% More Than*, Condition Value = 3
6. Multiply the condition value by the provided weight value and determine the sum for the three months.
7. Determine the overall rainfall condition and condition values as follows:
   - **Drier than Normal:** Sum is between 6 and 9.
     Infiltration testing during these conditions is unfavorable, recommend waiting until normal conditions resume or thoroughly wetting soil prior to testing.
   - **Normal:** Sum is between 10 and 14.
     Infiltration testing during these conditions is recommended.
   - **Wetter than Normal:** Sum is between 15 and 18.
     Infiltration testing during these conditions is acceptable.

4.1.3 Groundwater Mounding

The development of a groundwater mound can reduce the rate of percolation below the BMP (i.e., less hydraulic gradient to drive the flow of water) and can feed back to result in reduction in surface infiltration rates. Where subsurface conditions of the infiltration receptor would limit actual infiltration rates, infiltration tests are inherently inadequate to estimate the reduction that would occur. This is because the scale of infiltration tests tends to be much smaller than full-scale facilities, and testing can rarely be run for a duration long enough or with enough volume of water to generate a groundwater mound. In these cases, infiltration testing should be complemented with analysis of groundwater mounding conditions. The Groundwater Mounding Assessment Tool included in Appendix C has been designed to support estimates of when groundwater mounding would reduce infiltration rate, and to what degree. The Groundwater Mounding Assessment Tool also accounts for the geometry of the BMP, the hydraulic gradient resulting from ponded water in the BMP, and flow of water both laterally and vertically. This tool can be used to help translate soil properties (i.e., saturated hydraulic conductivity) to the actual drawdown rate of the BMP, while also accounting for the effects of mounding, if present.

4.1.4 Temperature

The rate of infiltration through soil is affected by the viscosity of water, which is temperature dependent. Infiltration rates will be greater at higher temperatures (Cedergren, 1997). Comparing winter and summer infiltration rates below a BMP in Pennsylvania, Emerson (2008) observed that wintertime infiltration rates were approximately half their peak summertime rates. Temperature is an important consideration when planning tests and interpreting results. If possible, testing should be conducted at a temperature that approximates the typical runoff temperatures for the site during the times when rainfall occurs. If this is not possible, then the results of infiltration tests should be adjusted to account for the difference between the temperature at the time of testing and the typical temperature of runoff when rainfall occurs. The measured infiltration can be adjusted by the ratio of the viscosity at the test temperature versus the typical temperature when rainfall occurs (Cedergren, 1997):

$$K_{typical} = K_{test}\left(\frac{\mu_{Test}}{\mu_{Typical}}\right)$$

Where:

$K_{Typical}$ = Infiltration rate expected at typical temperature

K_{Test} = Measured infiltration rate

$\mu_{Typical}$ = Viscosity of water at typical temperature

μ_{Test} = Viscosity of water at test temperature

4.1.5 Test Variability and Averaging

Infiltration rates tend to be lognormally distributed. In other words, variation of an order of magnitude (factor of 10) or more is not unusual within a study plot. The following general alternatives are suggested for averaging the results of multiple tests to develop design infiltration rates.

- Calculate the geometric mean of the data as an indication of the central tendency. When selecting the portion of the factor of safety that accounts for site variability (See Section 4.3), consider how variable the data are around the geometric mean.

  OR

- Use the lowest measurement obtained from 3 or more tests. Do not apply an additional factor of safety for site variability.

Note that local jurisdictions may require alternative methods.

4.2 Post-processing and Adjustments Associated with Interpretation of Test Results

There are three general categories of post-processing and adjustment needed, depending on test.

Direct Interpretation – The following tests allow direct interpretation based on the rate of water loss through the infiltrating surface after the test has stabilized. For these tests, the effects of three-dimensional infiltration processes are limited; the residual effects are similar or less than what would be expected in full-scale facilities.

- Large diameter single ring infiltrometers
- Double-ring infiltrometers
- Large-scale PIT Test

Interpretation with Simple Adjustment Factors – The following test can be used to estimate infiltration rate with simple ratio-based conversion factors to adjust for differences in wall to floor area in the test versus the full-scale design.

- Small-scale PIT Test – a multiplier of 0.6 to 0.8 is typical (correction factor of 1.3 to 1.7). Wall area makes up 40 to 60 percent of total wetted area in test geometry but only 10 to 20 percent of total wetted area in typical BMP geometry. Therefore, a ratio can be calculated as: (wetted area to footprint area ratio in full scale)/(wetted area to footprint area ratio in test) = 1.15/1.50 = 0.77.

Complex Equations to Isolate 1-Dimensional Infiltration. The following tests require more complex equations to control for three-dimensional infiltration processes and unsaturated flow processes.

- Small Diameter Single Ring Infiltrometer - Spreadsheet available via Hatt and LeCustoumer (2008)
- Dual Head Infiltrometer – Automated test execution and interpretation via vendor-supplied software.
- Modified Phillips-Dunne Infiltrometer – Automated test execution and interpretation via vendor-supplied software.
- MiniDisk Infiltrometer – Excel-based Macro for Interpretation of Results.
- Constant Head Well Permeameter – Equations available via Kindred (2017) following from Reynolds (2008).
- Aardvark Permeameter – Automated measurement and interpretation via vendor-supplied software.
- Guelph Permeameter – Vendor-supplied spreadsheet for interpretation.

Conversion from Horizontal to Vertical Directionality - For borehole-based tests, a conversion from horizontal to vertical infiltration rate may be required as explained in Sections 2 and 3. If soils are relatively homogeneous, an additional factor of safety multiplier of 2.0 is recommended (See Section 4.3) to account for minor stratification and particle arrangement. If soil layers have distinctly different permeability and tests did not isolate homogeneous soil layers, then an additional factor of safety multiplier of 5 to 10 may be warranted.

Inadequate Data to Support Interpretation. Inspection of testing results may reveal that there is inadequate data to support an estimate of infiltration rate. For example, in cases where highly layered soils exist, and tests did not isolate layers, then it may be impossible to reliably translate results to vertical infiltration rate. Figure 2 shows an example boring log and well diagram for a borehole permeameter test performed in highly layered soil. This test returned an estimated infiltration rate of 4.3 in/hr. However, closer inspection of this boring log revealed that the 10 to 15-foot test interval spanned highly variable soils (from gravely sand to sandy clay) and did not account for the increasingly dense/clayey layers near the bottom of this interval.

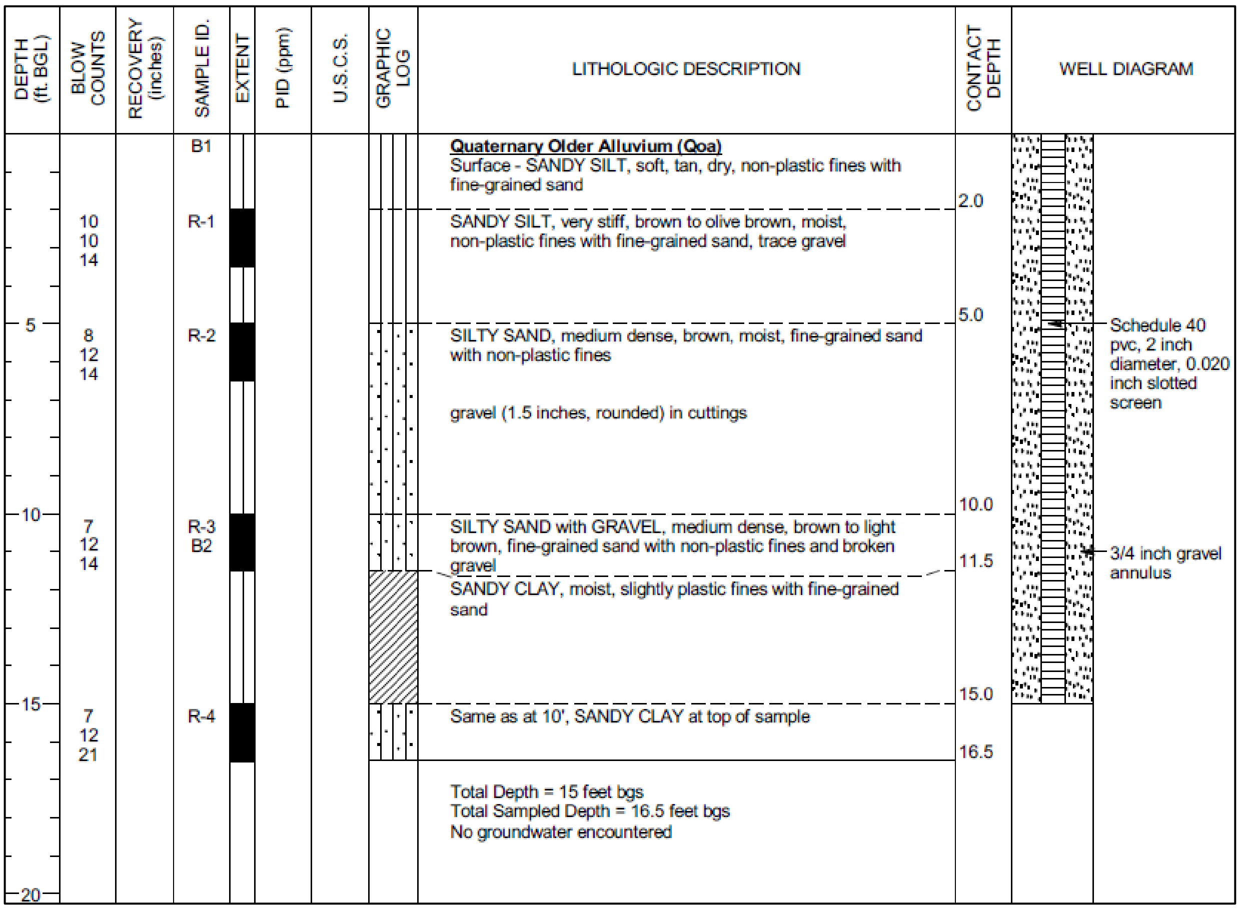

Figure 2. Example Boring Log and Well Diagram from a Borehole Permeability Test in Highly Layered Soils

4.3 Guidance for Factor of Safety Selection

The full-scale infiltration rate can be much lower than small-scale testing due to soil conditions not accounted for in infiltration tests, compaction during construction, clogging over time, groundwater mounding, and other factors. The objective of this section is to describe a framework for users to select a design factor of safety based on site suitability and design considerations. This guidance document is intended to be a supplemental guide to sound professional judgement and is not a substitute for local specifications on required factor of safety.

For each of the site suitability and design considerations, a qualitative high, medium, or low risk ranking is determined. These values are summed based on assigned weights to determine the design factor of safety (Section 4.3.5). Guidance on assigning concern levels and calculating the factor of safety is provided in the sections below.

After summing these qualitative values, two additional multipliers are added to account for quantitative factors, including the directionality of the test and the estimated effect of groundwater mounding per Appendix C.

4.3.1 Site Suitability Considerations for Factor of Safety Selection

Site suitability considerations are based on the uncertainty in the assessment of site conditions. A high, medium, or low concern designation is determined for the following considerations based on the description provided in Table 7:

1. **Soil Assessment Method:** The extent of testing (e.g., number of borings, test pits, etc.) and measurement method used to estimate the infiltration rate.
2. **Predominant Soil Texture/Percent Fines:** Soil texture and the percent of fines can influence the potential for clogging. Finer grained soils may be more susceptible to clogging.
3. **Site Soil Variability:** Sites with spatially heterogeneous soils (vertically or horizontally) as determined from site investigations are more difficult to estimate average properties for resulting in a higher level of uncertainty associated with initial estimates. If the lowest measured infiltration rate from at least 3 tests is being used and this represents the infiltration rate of the limiting vertical horizon, then do not apply an additional factor of safety for this factor.

Table 7. Site Suitability Factor of Safety Considerations

Consideration	Higher Concern Indicators	Lower Concern Indicators
Assessment Method	• Use of any test without accompanying bore log • Use of test poorly matched to conditions and BMP • Testing at different elevations or locations than proposed BMPs • Relatively sparse testing.	• Direct measurement with appropriate tests • Tests at recommended spacing/density • Accompanying bore logs
Texture Class	• Soils with significant fine-grained content (silts, silty loams)	• Granular to slightly loamy soils (sands, sandy loams)
Site Soil Variability	• Higher variability of soils indicated from site assessment (>10x difference between low and high), <u>OR</u> • Unknown variability due to lack of tests.	• Soil borings/test pits indicate relatively homogeneous soils (< 2x difference between low and high, <u>OR</u> • Lowest of at least three measurements are used.

4.3.2 Design Considerations for Factor of Safety Selection

Design considerations are intended to account for factors that affect the likelihood of compaction or clogging over time and to incorporate design features that allow for adaptability/resiliency. The Clogging Risk Assessment Tool (Appendix F) can be consulted to support evaluation of these factors. Determine a high, medium, or low concern designation as described in Table 8 corresponding with the following considerations:

1. **Influent Sediment Load/Pretreatment:** Facilities designed to capture runoff from relatively clean surfaces such as rooftops are likely to see low sediment loads compared to sites treating disturbed landscapes. Sites with enhanced pretreatment devices are at a lower risk of clogging due to less sediment reaching the infiltrative layer.
2. **Construction Compaction:** Proper construction oversight is needed to ensure that the bottoms of infiltration facilities are not impacted by significant incidental compaction. Facilities that use proper construction practices and oversight need less restrictive safety factors.
3. **Redundancy/Resiliency:** Facilities that consist of multiple subsystems operating in parallel such that parts of the system remains functional when other parts fail and/or bypass have less uncertainty due to the ability to implement corrective action. For example, a contingency plan is in place such that a full infiltration BMP could be converted to a biofiltration BMP with partial infiltration may justify a lower factor of safety**.**
4. **Storage Depth:** The storage depth of the infiltration BMP is the total equivalent water depth stored, after accounting for pore spaces. BMPs with deeper storage depths tend to have a higher sediment loading per unit area compared shallower BMPs, which may lead to greater clogging potential. The risk of prolonged drain times is greater for deeper BMPs if clogging does occur.

Table 8. Design factor of safety considerations

Consideration	**Higher Concern Indicators**	**Medium Concern Indicators**	**Lower Concern Indicators**
Influent Sediment Load/Pretreatment	Pretreatment is not provided <u>AND</u> Tributary area includes landscaped areas, steep slopes, high traffic areas, or any other areas expected to produce high sediment, trash, or debris loads.	Good pretreatment with BMPs that mitigate coarse sediments such as vegetated swales <u>AND</u> Influent sediment loads from the tributary area are expected to be moderate (e.g., low traffic, mild slopes, stabilized pervious areas, etc.).	Excellent pretreatment with BMPs that mitigate fine sediments such as bioretention or sedimentation basins <u>OR</u> Facility only treats runoff from relatively clean surfaces, such as rooftops or non-sanded road surfaces.
Construction Compaction	Construction of facility on a compacted site <u>OR</u> Elevated probability of unintended/ indirect compaction. (this scenario is strongly discouraged)	Low ground pressure equipment will be used for excavation <u>AND/OR</u> Medium probability of unintended/ indirect compaction.	Equipment traffic is effectively restricted from infiltration areas during construction <u>AND</u> Low probability of unintended/ indirect compaction.
Redundancy/ Resiliency	No redundancy in BMP treatment train <u>AND</u> No reasonable ability to adapt design if infiltration rates less than planned	The system has a backup pathway for treated water to discharge if clogging occurs <u>OR</u> Infiltration rates can be restored via maintenance.	The system has a backup pathway for treated water to discharge if clogging occurs <u>AND</u> Infiltration rates can be relatively easily restored via maintenance.

Consideration	Higher Concern Indicators	Medium Concern Indicators	Lower Concern Indicators
Storage Depth	Relatively deep profile (>4 feet).	Moderate profile (1 to 4 feet)	Shallow profile (< 1 ft)

4.3.3 Directionality

If a borehole test is used to estimate vertical infiltration rate, then an additional factor of safety multiplier of 2.0 is recommended. A higher factor may be warranted for sites with highly variable properties where the test did not isolate the limiting soil layer. An example of highly variable layers would be sand or gravel lens between layers of silty loam. The geotechnical professional should be consulted to evaluate whether any estimate of vertical infiltration rate can be made in this case.

4.3.4 Mounding Reduction

Based on the results of the Groundwater Mounding Assessment Tool (Appendix C), enter an additional reduction based on the average reduction estimate by the Tool for the conditions that best match or bracket the proposed BMP.

4.3.5 Factor of Safety Calculation

The design factor of safety is a correction to the measured short-term infiltration rate to account for uncertainty. When assigning a factor of safety, professional judgement should be used to understand any additional factors that may impact infiltration rate and avoid incorporating compounding factors of safety resulting in over-design. A suggested methodology for determining the design infiltration rate is determined as follows, corresponding with the worksheet in Table 9:

1. For each consideration shown in Table 7 and Table 8, determine whether the consideration is of high, medium, or low concern.
2. Assign factor values: high concern = 3, medium concern = 2, low concern = 1.
3. Multiply each factor by the corresponding assigned weight to get a product.
4. Sum the products within each factor category to obtain a safety factor for each.
5. Multiply the four safety factors together to get the final combined safety factor. If the combined safety factor is less than 2, then 2 shall be used as the safety factor.
6. Divide the measured short-term infiltration rate by the combined safety factor to obtain the adjusted design infiltration rate for use in sizing the infiltration facility.

To make BMPs more feasible and cost effective, steps should be taken to plan and construct infiltration BMPs in a way that will reduce the safety factors needed for those projects. A commitment to thorough site investigation, use of effective pretreatment controls, good construction practices, and restoration of previously compacted soils can lower the required factor of safety. For projects being designed under a regulatory mandate to conduct a rigorous infiltration feasibility screening and to select infiltration BMPs where feasible, it may be necessary to put an upper cap on the factor of safety that may be used as part of infeasibility screening. For example, in Orange County (CA), a factor of safety of 2.0 must be used for infiltration feasibility screening such that an artificially high factor of safety cannot be used to inappropriately rule out infiltration at a screening level. If the site passes the feasibility analysis at a factor of safety of 2.0, then infiltration must be investigated, but a higher factor of safety may be selected at the discretion of the design engineer. A similar approach may be useful for DOTs under similar regulatory conditions.

Table 9. Factor of safety and design infiltration rate worksheet

Category		Consideration	Assigned Weight (w)	Factor Value (v)	Product (p) p = w x v
A	Site Suitability	Assessment Method	0.25		
		Texture Class	0.25		
		Site Soil Variability	0.25		
		Suitability Assessment Safety Factor, $S_A = \Sigma p$ (ranges from 0.75 to 2.25)			
B	Design	Influent Sediment Load/Pretreatment	0.25		
		Construction Compaction	0.25		
		Redundancy/Resiliency	0.25		
		Storage Depth	0.25		
		Design Safety Factor, $S_B = \Sigma p$ (ranged from 1 to 3)			
Directionality Factor of Safety, S_C (ranges from 2 to 10)					
Groundwater Mounding Factor of Safety, S_D = 1/(Groundwater Mounding Reduction Factor) Groundwater Mounding Reduction Factor is the ratio of the actual infiltration rate divided by the nominal infiltration rate per the Groundwater Mounding Tool in Appendix C					
Combined Safety Factor, $S_{Total} = S_A \times S_B \times S_C \times S_D$					
Measured Infiltration Rate from Infiltration Tests, inch/hr, $K_{measured}$					
Design Infiltration Rate, in/hr, $K_{design} = K_{obs} / S_{Total}$					

Note: The minimum combined adjustment factor shall not be less than 2.0 and the maximum combined adjustment factor shall not exceed 9.0.

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Washington State Department of Ecology (WSDOE). (2012). *Stormwater Management Manual for Western Washington - Volume 3: Hydrologic Analysis and Flow Control BMPs.* Retrieved from https://fortress.wa.gov/ecy/publications/summarypages/1210030.html

Wisconsin Department of Natural Resources (WDNR). (2017). *Conservation Practice Standard 1002 – Site Evaluation for Storm Water Infiltration*. Wisconsin Department of Natural Resources. Madison, WI. Available at http://dnr.wi.gov/topic/Stormwater/standards/postconst_standards.html

Infiltration Testing Method Fact Sheets

Fact Sheet B.1 Simple Open Pit Test

Test Method Description

The Simple Open Pit Test is intended to support preliminary infiltration feasibility screening purposes. As its name implies, it involves digging a hole and monitoring the rate of water infiltration into the hole. This testing method focuses on efficiency over accuracy and transferability to full-scale design. It is not generally used to support estimation of a design infiltration rate.

Summary of Basic Field Test Steps

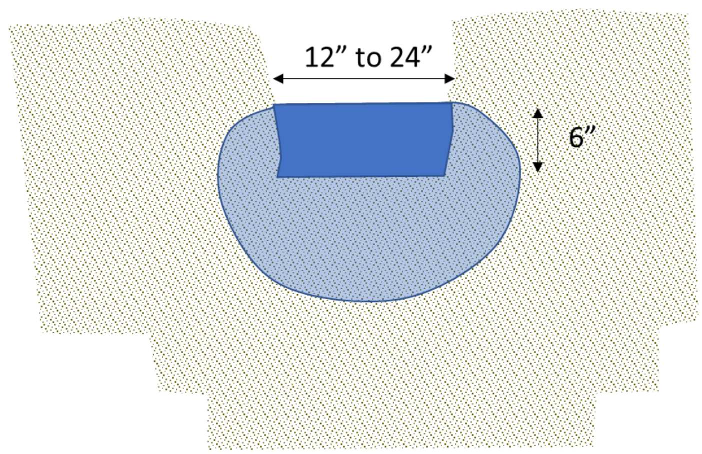
1. Excavate a test hole approximately 1 to 2 feet in diameter to a depth of 1 to 2 feet. Attempt to construct hole with relatively vertical walls and a flat bottom, however this is not critical.
2. Use a rake to scarify the sidewalls and floor.
3. Fill the hole to 6 inches of depth.
4. Using a simple depth rod or measuring tape, record water levels every 5 to 10 minutes for a minimum of 1 hour or until all the water has infiltrated.
5. Divide the distance of fall by the elapsed time to yield an estimated infiltration rate.

Method At-a-Glance

Method Type	Open Pit Test
Characteristic Measured	Rate of fall in a hole
Specialized Equipment	Backhoe (optional) shovel can be used in place)
Other Equipment and Supplies	Shovel, rake, water supply, tape measure, timer
Quantity of Water Used	100 to 250 gallons per test
Labor/Time Needs	1-2 people can attend to up to 4 tests at a time 2 to 4 hrs/test; can be run in parallel without extra equipment

Conceptual Test Dimensionality

[Dark blue: ponded water; Light blue: conceptual soil moisture bulb]



Method Interpretation

The rate of water level drop (i.e., in/hr) can be used directly to support a preliminary "go/no go" evaluation of infiltration feasibility. There is not typically a correction applied for side-wall infiltration, since results are not typically used for design.

Applicability and Limitations

- This method is typically a "go/no go" evaluation and is not typically a method used for design.
- Given the simplicity of the test, multiple locations can be tested simultaneously, allowing results to be used to inform BMP siting and assess site variability.
- Water movement is vertical and lateral. No connection for geometry as test is used primarily for preliminary screening.

Key Practitioner Notes

- Tests do not require much skill, equipment, or time therefore does not need to be conducted by a professional.
- If tests are conducted when soils are very dry, consider multiple sequential tests (up to three) at each location to evaluate whether infiltration rate declines as soils become wetter.
- While mechanical equipment is not needed, it can help expedite the test if it is available. .

Reference

City of Portland (2016) Section 2.3.6. https://www.portlandoregon.gov/bes/71127

Fact Sheet B.2 Small-Scale PIT Test

Test Method Description

The Small-Scale Pilot Infiltration Test (PIT) is intended to support either preliminary infiltration feasibility screening purposes or design purposes. Although it is similar to the simple open pit test, this test is more carefully controlled, is run for both constant head and falling head periods, and therefore provides more reliable estimates potentially suitable for design. Variations on this test offer similar information.

Basic Field Test Steps

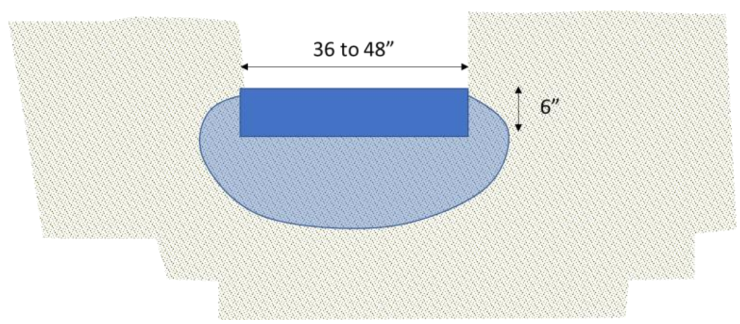
1. Excavate a rectangular, flat-bottomed test hole approximately 12 sq-ft to a depth of 1 to 2 ft. The bottom of the hole should be approximately equal to the grade of the proposed BMP.
2. Use a rake or the backhoe bucket to scarify the sidewalls and floor.
3. Pre-soak by filling the hole to 12 inches of depth and allowing to fully drain or soak up to 6 hours.
4. Refill to 6 inches of depth to start the test.
5. Maintain a constant head and record the flowrate needed to maintain the head. Run until the flowrate stabilizes.
6. After stabilizing, turn off the water and allow the pit to drain.
7. Using a simple depth rod or measuring tape, record water levels every 5 to 10 minutes for a minimum of 2 hours or until all the water has infiltrated.

Method At-a-Glance

Method Type	Open Pit Test
Characteristic Measured	Rate of fall in a hole
Specialized Equipment	Backhoe (typically required due to size of pits)
Other Equipment and Supplies	Shovel, rake, water supply, tape measure, timer
Quantity of Water Used	350 to 1,000 gallons per location
Labor/Time Needs	1-2 people can attend to up to 4 tests at a time 6 to 12-hour pre-soak 2 to 4 hrs/test; can be run in parallel without extra equipment

Conceptual Test Dimensionality

[Dark blue: ponded water; Light blue: conceptual soil moisture bulb]



Method Interpretation

The rate of infiltration (i.e., in/hr), with a correction fact of approximately 0.75 can used to estimate the measured infiltration rate for a typical basin-type BMP, accounting for the greater proportion of side slopes in the test compared to a proposed BMP.

Applicability and Limitations

- This method can be used to support design infiltration rates.
- It requires relatively large volumes of waters.
- When the BMP will be below grade, excavation quantities may be prohibitive.

Key Practitioner Notes

- Tests should be overseen by a professional, but limited special equipment or procedure is required.
- Pre-soaking can be initiated the night before to reduce the effective time required for the tests.

Reference: Eastern Washington Stormwater Management Manual. Washington State, 2013. Appendix B. http://www.wastormwatercenter.org/files/library/x100percentbooktest3meta-textremovedreduced.pdf

Fact Sheet B.3 Large Diameter Single Ring Infiltrometer

Test Method Description

The Large Diameter Single Ring Infiltrometer method typically uses a 12 to 36-inch diameter ring. Water is ponded within the ring above the soil surface with the upper surface of the ring covered to prevent evaporation (Riverside County, 2011). When performing the test with the constant head method, water is added at a constant rate with measurements taken until the flow rate has stabilized. Falling head methods can also be used.

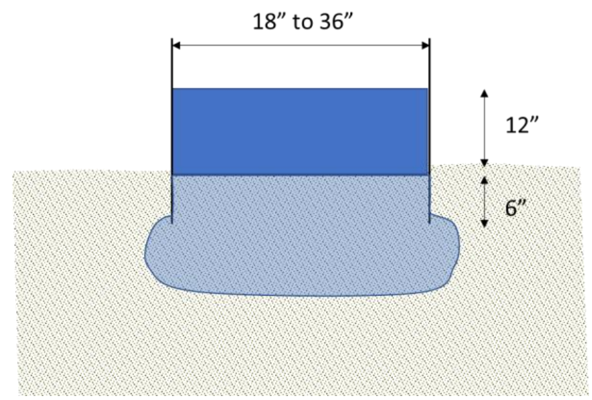
Method At-a-Glance	
Method Type	Surface Infiltrometer
Characteristic Measured	Rate of fall
Specialized Equipment	Single ring infiltrometer apparatus; flow meter/totalizer and Mariotte Tube (for constant head test only).
Other Equipment and Supplies	Water supply, hammer, measuring tape, timing device
Quantity of Water Used	50-200 gallons per test
Labor/Time Needs	1 to 2 people/8-12 hours; multiple tests can be run at the same time; however multiple apparatuses are needed.

Summary of Field Test Steps

1. Drive ring into soil to a depth of 6 inches. If separation occurs between the soil and the inside of the ring, loosely pack soil into this gap.
2. Presoak for 6 to hours, or until at least 12 inches of water has infiltrated.
3. For constant head:
   a) Add water at a rate that results in constant head.
   b) Record volume of water added over time.
4. For falling head:
   a) Fill to 6 inches of depth
   b) Record water levels every 5 to 10 minutes for a minimum of 2 hours or until all the water has infiltrated.
5. The test is completed once the loss rate has stabilized for a period of 1 to 2 hours.

Conceptual Test Dimensionality

[Dark blue: ponded water; Light blue: conceptual soil moisture bulb]



Method Interpretation

Rate of fall is used directly to estimate near-surface infiltration rate of soil after results of sequential trials have stabilized. This provides a reasonable estimate of near-surface vertical saturated hydraulic conductivity. For smaller diameter tests, additional corrections may be needed.

Applicability and Limitations

- This method measures the vertical hydraulic conductivity at the surface of the soil filter media.
- This primarily isolates the vertical component of water movement. The single ring allows for some lateral movement of water below ground.

Key Practitioner Notes

- Not appropriate for systems where the controlling layer is not the surface layer.
- Tests should be conducted at three points that are spatially distributed within the proposed BMP. It is essential that the monitoring areas are flat and level.
- The cost and ease of use of this method, with the appropriate number of tests, provides a good estimate of BMP design exfiltration rates.

Reference: Riverside County Flood Control and Water Conservation District, (Riverside County). (2011). Design Handbook for Low Impact Development Best Management Practices Appendix A – Infiltration Testing. Riverside, CA. http://www.floodcontrol.co.riverside.ca.us/NPDES/LIDBMP.aspx

Fact Sheet B.4 Double Ring Infiltrometer

Test Method Description

The Double Ring Infiltrometer is used to measure the soil infiltration rate at the ground surface. The apparatus consists of an inner and outer ring, typically 12 and 24 inches, respectively. A constant head method is used to run the test. For a constant head test, water is constantly added to both rings throughout the test, and the volume of water is measured at each time interval. A flow totalizer or graduated vessel is used to estimate the total volume of water added in each time interval. A Mariotte Tube can be used to maintain constant head.

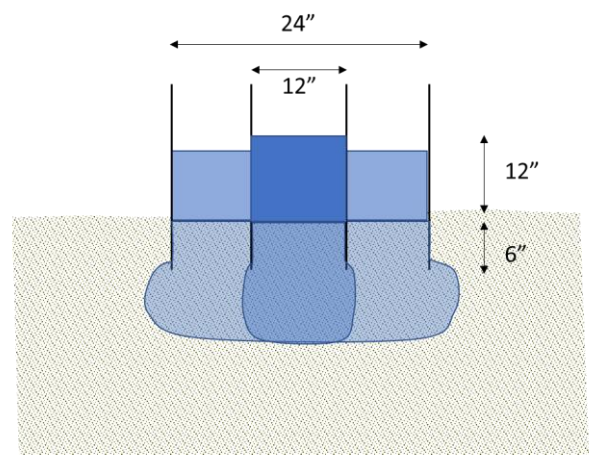
Method At-a-Glance	
Method Type	Surface Infiltrometer
Characteristic Measured	Vertical, near-surface saturated infiltration rate
Specialized Equipment	Double-ring apparatus. Mariotte tube to maintain water level, flow meter or totalizing device
Other Equipment and Supplies	Thermometer, pH paper, driving plate/hammer
Quantity of Water Used	100 to 300 gallons
Labor/Time Needs	2 people, 12 -24-hrs/test; multiple tests can be run at the same time, however multiple apparatuses are needed

Summary of Field Test Steps

1. Drive rings into soil and set up water supply system.
2. Presoak both rings for 12 hours, or until 12 inches of water have infiltrated. A presoaking period is used to reduce the length of time needed for readings to stabilize once the test has started.
3. Measure rate of water addition into the inner ring.
4. Record the rate or volume of water at 5 to 10-minute increments (may be lengthened for slowly draining soils).
5. Once results have stabilized (10% declined over a 2-hour period), discontinue the trial.

Conceptual Test Dimensionality

[Dark blue: ponded water; Light blue: conceptual soil moisture bulb]



Method Interpretation

Rate of fall is used directly to estimate near-surface infiltration rate after results of sequential trials have been stabilized. This is a reasonable estimate of near-surface vertical saturated hydraulic conductivity.

Applicability and Limitations

- This test method is particularly applicable to relatively uniform fine-grained soils, with an absence of very plastic (fat) clays and gravel-size particles and with moderate to low resistance to ring penetration.
- Theoretically, this test best isolates vertical infiltration rates.

Key Practitioner Notes

- In hard soils, rings can be difficult to drive, and soils can fracture/separate from the rings.
- In the experience of practitioners interviewed to develop this fact sheet, the double ring method is typically more complex, more expensive, and does not necessarily improve the reliability of the measurement for uses related to infiltration BMPs.

Reference

ASTM International. (2009). ASTM Standard D3385-09, Standard Test Method for Infiltration Rate of Soils in Field Using Double-Ring Infiltrometer. http://www.astm.org/Standards/D3385.htm

Fact Sheet B.5 Dual Head Infiltrometer

Test Method Description

The DualHead Infiltrometer is a proprietary, single ring infiltrometer device sold by Decagon Devices. The device measures three-dimensional field saturated hydraulic conductivity in under two different ponding depths. The hydraulic conductivity is derived from the difference in infiltration rate at these depths. The Dual Head Infiltrometer consists of four main components; the Infiltrometer Head, Control Unit, Insertion Ring and water supply. (Decagon Devices, Inc. 2016a).

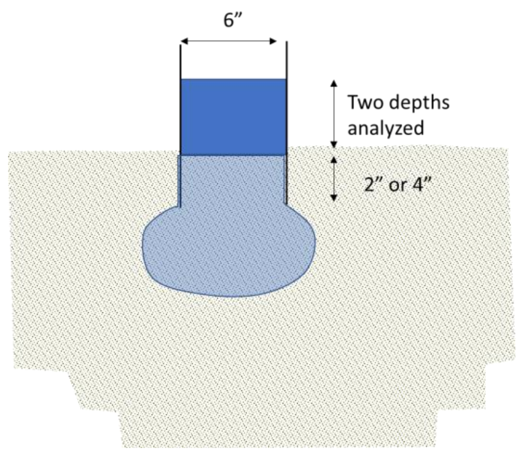
Method At-a-Glance	
Method Type	Proprietary Infiltrometer
Characteristic Measured	Rate of water infiltration into soils under controlled head conditions
Specialized Equipment	Dual Head Infiltrometer Kit (fully automated readings and calculations)
Other Equipment and Supplies	Mallet and water supply
Quantity of Water Used	5 gallons per test
Labor/Time Needs	1 person/1.5-3 hours per test – a device supports one test at a time.

Basic Field Test Steps

1. Set up control unit.
2. Place insertion ring on the ground at desired test location. Fit driving plate onto insertion ring.
3. Set up infiltrometer head and set water tank beside controller and open water valve.
4. Power on device, set determined parameters and run test.
5. The device software automatically applies water, calculates the rate/volume applied and performs calculations to calculate the saturated hydraulic conductivity.
6. The device automatically conducts trials at both heads.

Conceptual Test Dimensionality

[Dark blue: ponded water; Light blue: conceptual soil moisture bulb]



Method Interpretation

The final infiltration rate is measured for each of two ponding depths. The difference in infiltration rates at these heads is used to calculate the saturated hydraulic conductivity. This corrects for 3-dimensional and unsaturated soil effects.

Applicability and Limitations

- The Dual Head Infiltrometer will generally be able to make measurements on poorly to moderately structured soils as coarse as medium sand.
- The maximum infiltration rate supported by the device can be exceeded by soils with excessive structure and especially soils with significant macropore flow.
- The range of values that can be effectively measured by the Dual Head Infiltrometer are limited by the minimum and maximum infiltration rates of 0.0015 in/hr to 45.28 in/hr.

Key Practitioner Notes

- Comparatively less labor-intensive method than non-proprietary ring infiltrometers as steps are automated.
- The Dual Head Infiltrometer uses the multiple head analysis approach to correct 3-dimensional flow without having to make assumptions regarding soil absorptivity and the soil macroscopic capillary length. This allows a more accuracy without a pre-soaking period.
- The testing unit is fairly heavy and can be difficult to maneuver in the field.
- Results are computerized, which reduces error in manual computations.

Reference: Decagon Devices, Inc. (2016a). DualHead Infiltrometer Manual. http://www.decagon.com/en/hydrology/hydraulic-conductivity/dualhead-infiltrometer/#Support

Fact Sheet B.6 Modified Philip-Dunne (MPD)

Test Method Description

The Modified Philip-Dunne (MPD) falling head infiltrometer was developed for measuring surface infiltration rates in stormwater best management practices. The MPD consists of a hollow cylinder that is simply inserted into the soil surface (Nestingen, 2007). The rate of fall in the system is tracked incrementally. Based on the pattern of the fall of the water surface, algorithms associated with the MPD are used to calculate the saturated hydraulic conductivity of near-surface soils. The theory is similar to the Dual Head Infiltrometer and other methods that involve testing at varying head.

Method At-a-Glance	
Method Type	Proprietary Infiltrometer
Characteristic Measured	Hydraulic conductivity of surface soil material
Specialized Equipment	MPD Infiltrometer Kit (fully automated readings and calculations)
Other Equipment and Supplies	Hammer, water supply
Quantity of Water Used	6 gallons
Labor/Time Needs	1 person/ 1-2 hrs/test

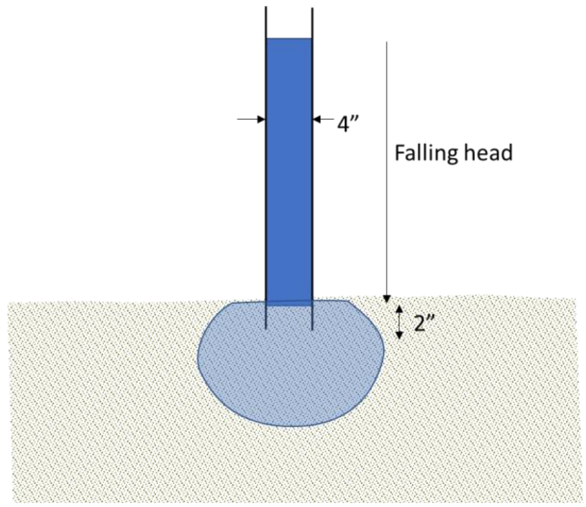
Basic Field Test Steps

1. Insert Infiltrometer into soil so that it will rest on the soil surface at a depth of 2 inches.
2. Fill device to a predetermined initial height. As soon as the device is filled to the desired level, a stopwatch is started and the height of water in the cylinder is recorded in respect to time.
3. Record head in device over time. Typically, 12 to 15 readings for a location are desired for an accurate optimization of hydraulic conductivity.
4. The head vs. time readings, initial and final volumetric moisture contents, are then entered into the MPD software to determine hydraulic conductivity and capillary pressure at the wetting front.

(Note: the MPD Kit automates the measurement and calculations.)

Conceptual Test Dimensionality

[Dark blue: ponded water; Light blue: conceptual soil moisture bulb]



Method Interpretation

The rate and pattern of water level fall is measured. The soil gravimetric final moisture content is measured from the porosity of the soil and then converted to the volumetric moisture content by multiplying it with the dry bulk density of the soil. Saturated hydraulic conductivity is calculated based on the computer software associated with the product.

Applicability and Limitations

- Generally applicable for stormwater applications.
- Like other infiltrometers, this method primarily measures near-surface soil properties.

Key Practitioner Notes

- Because it is a falling head test, it requires less water than other tests.
- The automated system requires little manual efforts.
- Multiple tests can be run simultaneously with multiple MPD heads. Some equipment, such as the electronic tablet, moisture meter can be shared across multiple tests.

Reference

Ahmed, F., Gulliver, J. S., & Nieber, J. L. (2011). Performance of Low Impact Development Practices on Stormwater Pollutant Load Abatement, Appendix C: Manual for the Modified Philip-Dunne (MPD) Infiltrometer. University of Minnesota St. Anthony Falls Laboratory. Prepared for Minnesota Pollution Control Agency. August 2011. https://www.pca.state.mn.us/sites/default/files/p-gen3-13t.pdf

Fact Sheet B.7 Mini Disk Infiltrometer

Test Method Description

The Mini Disk Infiltrometer measures the unsaturated hydraulic conductivity of soil. The upper and lower chambers of the infiltrometer are both filled with water. The top chamber (or bubble chamber) controls the suction while the lower chamber contains a volume of water that infiltrates into the soil at a rate determined by the suction selected in the bubble chamber (Decagon Devices, 2016b). The offsets the effect of the suction forces of the soil, allowing unsaturated hydraulic conductivity to be isolated.

Method At-a-Glance

Method Type	Proprietary Infiltrometer
Characteristic Measured	Unsaturated hydraulic conductivity
Specialized Equipment	Mini Disk Infiltrometer Kit
Other Equipment and Supplies	N/A
Quantity of Water Used	1 gallon
Labor/Time Needs	1 person/ 0.5-5 hrs/test

Basic Field Test Steps

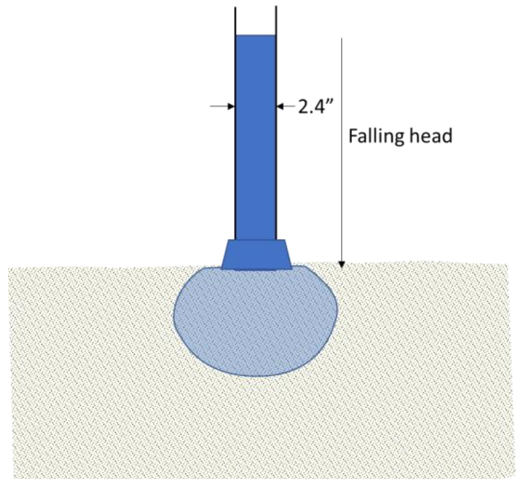
1. Fill bubble chamber with water and choose suction rate based on the suction head typical of the soil texture class (guidance is provided by the vendor).
2. Place infiltrometer on smooth soil surface without any irregularities.
3. Record starting water volume and volume at regular time intervals as water infiltrates.
4. Calculate hydraulic conductivity.

Method Interpretation

In-situ hydraulic conductivity is calculated based on the cumulative infiltration volume and input parameters for the soil type following methods detailed by the manufacturer. The volume is converted to depth of water infiltrated by subtracting the starting volume reading and dividing by the area of the disk on the Infiltrometer.

Conceptual Test Dimensionality

[Dark blue: ponded water; Light blue: conceptual soil moisture bulb]



Applicability and Limitations

- The Mini Disk Infiltrometer measures the unsaturated hydraulic conductivity of the medium it is placed on at different applied tensions.
- Due to its compact size, the water needed to operate it can easily be carried in a small vessel.
- Data is only provided at the surface.
- Results may not represent full-scale saturated infiltration processes below BMPs.

Key Practitioner Notes

- The Infiltrometer has an adjustable suction ranging from approximately 0.2 to 3 inches that provides additional information about the soil by eliminating macropores with an air entry value smaller than the suction of the infiltrometer.
- The small surface area provides an estimate of the soil hydraulic conductivity at an isolated location. Multiple tests should be conducted in various locations to account for spatial variation and increase confidence in results.

Reference

Decagon Devices, Inc. (2016b). Mini Disk Infiltrometer Manual. http://www.decagon.com/en/hydrology/hydraulic-conductivity/mini-disk-portable-tension-infiltrometer/#Support

Fact Sheet B.8 Constant Head Well Permeameter

Test Method Description

There are a wide range of Well Permeameter methods. This fact sheets intended to describe the general outline of a constant head well permeameter (CHWP) testing protocol (Reynolds, 2008).

This test is an in-hole hydraulic conductivity test that is performed by drilling test wells with a 6 to 8-inch diameter auger to the desired depth. The test measures the rate at which water flows into the soil under constant head which is then used, along with the dimensionality of the test and information about the soil texture, to estimate the in situ saturated hydraulic conductivity.

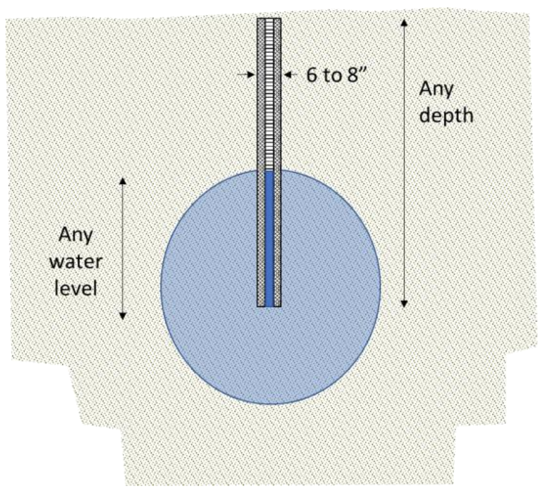
Method At-a-Glance	
Method Type	Borehole Permeameter
Characteristic Measured	Measures hydraulic conductivity (primarily horizontal) of a soil layer
Specialized Equipment	Drilling rig, transducer or other water level sensor, float, float guide
Other Equipment and Supplies	Thermometer, water truck, water reservoir
Quantity of Water Used	Depends on permeability, diameter, length of screened interval and duration of test. Example: 200 to 1,000 gallons for 5-foot screened interval, 8-inch dia, 6-hour duration, in moderate to permeable soil.
Labor/Time Needs	2 people/minimum 4 hrs/test

Summary of Basic Field Test Steps

1. Drill test wells to desired depth and install the monitoring well, including casing and packing.
2. Log the boreholes.
3. The well casing can be screened over the entire depth or the screened interval can be limited to a certain depth range.
4. A pressure transducer or other level sensor is used to measure water level from a fixed datum.
5. The well is filled to the desired level, and then the water level is maintained at the target level using a float or other method.
6. Cumulative water volume is tracked versus time until the loss rate stabilizes (less than 10% reduction over 2 hours).

Conceptual Test Dimensionality

[Dark blue: ponded water; Light blue: conceptual soil moisture bulb]



Method Interpretation

A range of methods can be used to interpret the saturated hydraulic conductivity of the soil based on the geometry of the test, the head on the soil, and the water temperature. A conversion from a 3-dimensional percolation rate to 1-dimensional saturated hydraulic conductivity is needed. Corrections assume that soil is uniform within the testing interval. This assumption should be confirmed via interpretation of bore logs.

Applicability and Limitations

- This test measures the rate at which water flows into the soil under constant-head conditions. Directionality is primarily lateral.
- These results are used in appropriate equations for calculating approximate 1D horizontal and vertical infiltration.

Key Practitioner Notes

- Each distinct layer of soil should be tested individually. This can significant effort. Therefore, in layered soils, this test can be prohibitively expensive for estimating vertical hydraulic conductivity.
- This test should be performed by a qualified professional, such as a hydrogeologist or geotechnical engineer.

Reference: Kindred, S. (2017). Improved Methods for Stormwater Infiltration Testing: Borehole Permeameter Method. *Proceedings of StormCon*, August 2017. Seattle, Washington. http://www.stormcon.com/wp-content/uploads/2017/10/Kindred_R81.pdf

Fact Sheet B.9 Aardvark Permeameter

Test Method Description

The Aardvark Permeameter is a small-scale, proprietary version of the CHWP (Fact Sheet A.8). It uses a down-hole float valve to maintain a constant water level. This device estimates soil hydraulic conductivity by measuring the amount of supplied water measured at equal time intervals, as recorded by a weighing scale. The measurement ends when the reservoir flow rate does not change over several consecutive readings. Soil hydraulic conductivity then can be calculated using this steady flow rate.

Summary of Basic Field Test Steps

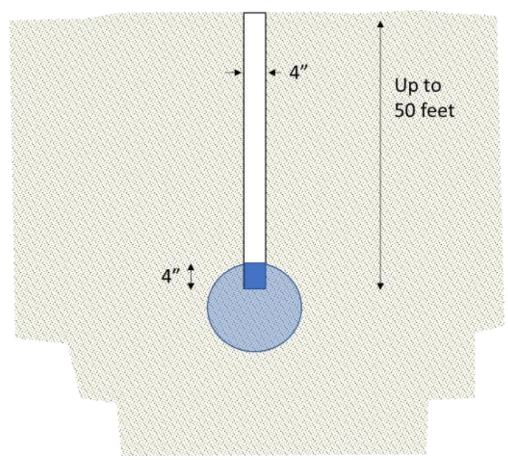
1. Excavate a 4-inch diameter borehole to the target depth. assemble reservoir unit and fill with water.
2. Assemble Aardvark table and place next to borehole.
3. Install the head of the Aardvark assembly in the borehole and record depth of borehole and height of reservoir.
4. Record the rate of discharge from the water reservoir into the borehole. Add more water if necessary and determine water consumption rate.
5. Continue until water consumption stabilizes over a period of at least 30 minutes.

Method At-a-Glance

Method Type	Proprietary Borehole Permeameter
Characteristic Measured	In-situ saturated water flow, lateral soil hydraulic conductivity
Specialized Equipment	Aardvark Permeameter Kit
Other Equipment and Supplies	Auger, backup water supply
Quantity of Water Used	5-10 gallons per test
Labor/Time Needs	1 person/1-2 hrs/test (each test requires a separate device, but multiple could be run at one time)

Conceptual Test Dimensionality

[Dark blue: ponded water; Light blue: conceptual soil moisture bulb]



Method Interpretation

Steady state flow rate is determined and can then be used to calculate the saturated hydraulic conductivity of the soil based on equations provided by the manufacturer.

Applicability and Limitations

- This method can be applied rapidly at multiple locations and depths.
- When care is taken to isolate vertical strata, this can provide a reasonable estimate of horizontal and vertical hydraulic conductivity with depth.
- The conversion calculation requires uniform soils. Soil layering should be established before testing. Then test intervals should be applied to uniform soil layers.

Key Practitioner Notes

- Before making a measurement, it is recommended to perform site and soil evaluation and log boring so that tests can be targeted to distinct soil layers.
- In most soils, a hand augur can be used to approximately 5 feet of depth, reducing the need for a drill rig.
- Windy days may impact readings by making the water level difficult to read and impact the accuracy of the digital scale.

Reference

Eijkelkamp Agrisearch Equipment. (2016). Aardvark Permeameter Operating Instructions. Model 2840. https://en.eijkelkamp.com/products/field-measurement-equipment/aardvark-automatic-permeameter.html

Fact Sheet B.10 Guelph Permeameter

Test Method Description

The Guelph Permeameter is a proprietary device used to measure in-situ hydraulic conductivity via constant head well permeameter methods. Similar to other CHWP methods, this method involves measuring the steady-state rate of water recharge into unsaturated soil from a cylindrical well hole, in which a constant depth of water is maintained. The Guelph permeameter is an in-hole Mariotte bottle device for measuring the infiltration rate into most types of soil or other porous medium. It has accompanying computational methods for interpreting results.

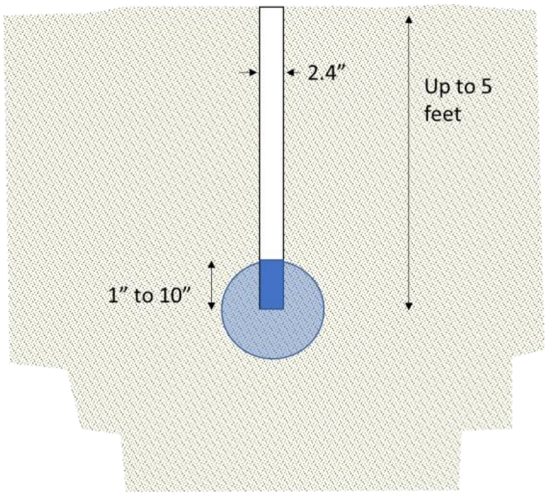
Method At-a-Glance	
Method Type	Proprietary Borehole Permeameter
Characteristic Measured	Soil hydraulic conductivity (primarily horizontal)
Specialized Equipment	Guelph Permeameter Kit
Other Equipment and Supplies	Auger, water supply and water container
Quantity of Water Used	3 to 10 gallons (depending on wetted depth, diameter, and soil permeability)
Labor/Time Needs	1 person/ 0.5-2 hrs/test (up to two tests could typically be done at a time in close proximity)

Summary of Basic Field Test Steps

1. Excavate borehole, assemble permeameter, and check for leaks. Wells are 2.4-inch diameter, up to 5 feet deep.
2. Fill the permeameter with water and insert it in the well. Under certain circumstances, the permeameter may have to be filled after it is placed in the well. Place tripod over well hole and establish well head height.
3. Record water level in reservoir. Monitor the rate of fall of the liquid surface in the reservoir until a steady rate is attained.

Conceptual Test Dimensionality

[Dark blue: ponded water; Light blue: conceptual soil moisture bulb]



Method Interpretation

The measured steady-state flowrate along with the diameter of the well, and height of the water in the well can be used to estimate the field saturated conductivity, flux potential, and absorptivity of the soil based on accompanying calculations specific to the device.

Applicability and Limitations

- This method can be applied rapidly at multiple locations and depths.
- Measurements can be made in the range of 6 to 61 inches below the soil surface.
- The typical conversion calculation assumes uniform soils.
- Soil layering should be established before testing. Then test intervals should be applied to uniform soil layers.

Key Practitioner Notes

- Before making a measurement, it is recommended to perform site and soil evaluation and log boring so that tests can be targeted to distinct soil layers.
- A hand augur can be used to develop the boreholes.
- Manual measurements are needed but can then be entered into a vendor-provided spreadsheet for calculations.

Reference: Eijkelkamp Agrisearch Equipment. (2011). Guelph Permeameter Operating Instructions. Model 2800. https://en.eijkelkamp.com/products/field-measurement-equipment/guelph-constant-head-permeameter.html