Appendix B – Methods for Determining Design Infiltration Rates

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B.1 Determining Design Infiltration Rates – Overview

The following methods are based on the requirements outlined in the SWMMWW, Volume III, Section 3.3.6. However, to improve clarity and usability and to remove inconsistencies in the SWMMWW, the information in this appendix has been organized in a slightly different structure. Therefore, although the following is equivalent to the SWMMWW, users shall use this appendix for work in the city.

B.1.1 Methods

There are two acceptable methods for estimating the measured (a.k.a., initial) saturated hydraulic conductivity (Ksat) rate at a site, outlined below and described in detail in Sections 3 and 4 of this appendix. A correction factor is applied to the initial rate to determine the design (long-term) infiltration rate (see Section 2). The design (long-term) infiltration rate is then used for routing and sizing the infiltration facility, and for checking for compliance with the maximum drawdown time of 48 hours. Note that the subgrade correction factors in this appendix (see Section 2) may not apply to bioretention, permeable pavement, and rain gardens. Refer to SWMMWW Volume III, Section 3.4 and Addendum Checklist 5 for additional guidance on infiltration testing methods and application of appropriate correction factors specific to bioretention, rain gardens, and permeable pavement.

- Method 1. Field Testing Procedures:
  - Large-Scale Pilot Infiltration Test (PIT). This test applies to infiltration facilities with drainage areas greater than 1 acre (i.e., projects that are using the “Detailed Method” – see Addendum Checklist 6 and SWMMWW Volume III, Section 3.3.5) and may be used to demonstrate infeasibility of bioretention, rain gardens, or permeable pavement in meeting Minimum Requirement No. 5.
  - Small-Scale PIT. This test applies to infiltration facilities with drainage areas less than 1 acre (i.e., projects that are using the “Simple Method” – see Addendum Checklist 6 and SWMMWW Volume III, Section 3.3.5) and may be used to demonstrate infeasibility of bioretention, rain gardens, or permeable pavement in meeting Minimum Requirement No. 5.
  - U.S. EPA Falling Head Percolation Test Procedure (as Modified for the City of Edmonds). This test may only be used for BMP performance verification testing. This test may not be used for BMP design; or to demonstrate infeasibility of bioretention, rain gardens, or permeable pavement in meeting Minimum Requirement No. 5.
- Method 2. Soil Grain Size Analysis: This method may only be used at project sites that are underlain by soils not consolidated by glacial advance (e.g., recessional outwash soils) and may not be used to demonstrate infeasibility of bioretention, rain gardens, or permeable pavement in meeting Minimum Requirement No. 5.

B.1.2 Number and Location of Tests

The following summarizes requirements related to the number and location of infiltration tests for specific BMPs. Users should refer to the individual BMP descriptions in SWMMWW Volumes III and V for additional details.

In addition to the requirements outlined in this section, note that for all BMPs, the depth and number of test holes or test pits and samples should be increased, if in the judgment of a professional engineer with geotechnical expertise (licensed in the State of Washington), a licensed geologist, licensed engineering geologist registered in the State of Washington, or hydrogeologist, the conditions are highly variable and such increases are necessary to accurately estimate the performance of the infiltration system. The exploration program may also be decreased if, in the opinion of a professional engineer licensed in the State of Washington in civil engineering, or licensed engineering geologist registered in the State of Washington, the conditions are relatively uniform and the borings/test pits omitted will not influence the design or successful operation of the facility. In high water table sites, the subsurface exploration sampling need not be conducted lower than 2 feet below the ground water table.

Projects shall perform the type and number of tests in accordance with specific BMP requirements in the SWMMWW, summarized below:

- Allowable methods:
    - As noted in Section 1, only small-scale and large-scale PITs are allowed to demonstrate infeasibility of bioretention, permeable pavement, and rain gardens (in accordance with Minimum Requirement No. 5). Other methods outlined in this appendix (and SWMMWW Volume III, Section 3.3.6) may be used to determine the design infiltration rate of underlying soils for these BMPs, but may not be used to demonstrate infeasibility. Therefore, the summaries below refer to PIT methods as a first preference for measuring infiltration rates for these three BMPs. Projects should consider the specific BMPs proposed (or anticipated) for a site, and the associated testing requirements, when planning and performing infiltration testing.
    - When using grain size analyses to measure infiltration rates, perform the number of test pits described below. Conduct at least one grain size analysis per soil stratum in each test hole within 2.5 times the maximum design water depth, but not less than 10 feet below the proposed base of the infiltration facility.
- Infiltration Basins: at least one test pit or test hole per 5,000 square feet of basin infiltrating surface (in no case less than two per basin).
- Infiltration Trenches (does not include downspout infiltration): at least one test pit or test hole per 200 feet of trench length (in no case less than two per trench).
- Bioretention:
    - For small bioretention cells (bioretention areas receiving water from one or two individual lots or <0.25 acre of pavement or other impervious surface): at least one small-scale PIT, or other method outlined in this appendix, at each potential bioretention site.

  - For large bioretention cells (bioretention areas receiving water from several lots or 0.25 acre or more of pavement or other impervious surface): at least one small-scale PIT, or other method outlined in this appendix, per 5,000 square feet of bioretention area.

  - For bioretention swales or long, narrow bioretention areas: at least one small-scale PIT, or other method outlined in this appendix, every 200 linear feet and within each length of road with varying subsurface characteristics.

- Permeable Pavement:

  - For projects subject for Minimum Requirement No. 1 through 5: at least one small-scale PIT, or other method outlined in this appendix, per 5,000 square feet of permeable pavement (in no case less than one test per site).

  - For projects subject for Minimum Requirement No. 1 through 9, commercial property: at least one small-scale PIT, or other method outlined in this appendix, per 5,000 square feet of permeable pavement (in no case less than one test per site).

  - For projects subject for Minimum Requirement No. 1 through 9, residential development: at least one small-scale PIT, or other method outlined in this appendix, at every proposed lot, every 200 linear feet of roadway, and within each length of road with significant differences in subsurface characteristics.

- Rain Gardens: at least one small-scale PIT, or other method outlined in this appendix, at each potential rain garden site.

B.2 Correction Factors

The Ksat obtained from the field tests or soil grain analyses is a measured (initial) rate. This measured rate must be reduced through correction factors that are appropriate for the design situation to produce an acceptable design infiltration rate. This adjustment is made in Step 5 of the Design of Infiltration Facilities (SWMMWW Volume III, Section 3.3.4 Steps for the Design of Infiltration Facilities – Simplified Approach [also summarized in Addendum Checklist 6]). Note that the correction factors below may not apply to the infiltration testing conducted for bioretention, permeable pavement, and/or rain gardens (see Volume III, Section 3.4 and Addendum Checklist 5 for additional information).

The following equation estimates the maximum design infiltration rate ($Ksat_{design}$) using correction factors to account for site variability, number of tests conducted, uncertainty of test method, and the potential for long-term clogging due to siltation and bio-build up. The specific correction factors used shall be determined based on the professional judgment of the site designer, considering all issues that may affect the infiltration rate over the long term, subject to the approval of the City.

$$Ksat_{design} = Ksat_{initial} \text{ x } CF_V \text{ x } CF_T \text{ x } CF_M$$

Table B.1. Correction Factors to be Used With In-Situ Saturated Hydraulic Conductivity Measurements to Estimate Design Rates.

Issue	Partial Correction Factor
Site variability and number of locations tested (CF_v)	CF_v = 0.33 to 1.0
Test Method (CF_T) • Large-scale PIT • Small-scale PIT • Other small-scale (e.g., Double ring, falling head) • Grain Size Method	$CF_{T:}$ • CF_T = 0.75 for Large-scale PIT • CF_T = 0.5 for Small-scale PIT • CF_T = 0.4 for other small-scale test • CF_T = 0.4 for Grain Size Method
Degree of influent control to prevent siltation and bio-buildup	CF_M = 0.9

Site Variability and Number of Locations Tested (CFv):

The number of locations tested must be capable of producing a picture of the subsurface conditions that fully represents the conditions throughout the facility site. The partial correction factor used for this issue depends on the level of uncertainty that adverse subsurface conditions may occur. If the range of uncertainty is low – – for example, conditions are known to be uniform through previous exploration and site geological factors – – one field test (or grain size analysis location) may be adequate to justify a partial correction factor at the high end of the range.

If the level of uncertainty is high, a partial correction factor near the low end of the range may be appropriate. This might be the case where the site conditions are highly variable due to conditions such as a deposit of ancient landslide debris, or buried stream channels. In these cases, even with many explorations and several field tests (or several grain size test locations), the level of uncertainty may still be high. A partial correction factor near the low end of the range could be assigned where conditions have a more typical variability, but few explorations and only one field test (or one grain size analysis location) is conducted. That is, the number of explorations and tests conducted do not match the degree of site variability anticipated.

Uncertainty of Test Method (CF_T):

CF_T accounts for uncertainties in the testing methods. For the full-scale PIT method, $CF_T = 0.75$; for the small-scale PIT, $CF_T = 0.50$; for smaller-scale infiltration tests such as the falling head percolation test method, $CF_T = 0.4$; for grain size analysis, $CF_T = 0.40$. These values are intended to represent the difference in each test's ability to estimate the actual saturated hydraulic conductivity. The assumption is the larger the scale of the test, the more reliable the result.

Degree of Influent Control to Prevent Siltation and Bio-Buildup (CF_M):

Even with a pre-settling basin or a basic treatment facility for pre-treatment, the soil's initial infiltration rate will gradually decline as more and more stormwater, with some amount of suspended material, passes through the soil profile. The maintenance schedule calls for removing sediment when the facility is infiltrating at only 90 percent of its design capacity. Therefore, a correction factor, CF_M, of 0.9 is called for.

B.3 Method 1 – Field Testing Procedures

B.3.1 Large-Scale Pilot Infiltration Test (PIT)

Large-scale in-situ infiltration measurements, using the PIT method described below, is the preferred method for estimating the measured (initial) saturated hydraulic conductivity (K_{sat}) of the soil profile beneath the proposed infiltration facility. The PIT method reduces some of the potential scale errors associated with relatively small-scale tests (such as the modified falling head percolation test, double ring infiltrometer, or "stove-pipe" infiltration tests). It is not a standard test but rather a practical field procedure recommended by the Washington Department of Ecology's Technical Advisory Committee. The PIT method is performed as follows:

Infiltration Test:

1. Excavate the test pit to the depth of the bottom of the proposed infiltration facility. Lay back the slopes sufficiently to avoid caving and erosion during the test. Alternatively, consider shoring the sides of the test pit.

2. The horizontal surface area of the bottom of the test pit should be approximately 100 square feet.

3. Accurately document the size and geometry of the test pit.

4. Install a vertical measuring rod (minimum 5 feet long) marked in half-inch increments in the center of the pit bottom.

5. Use a rigid 6-inch-diameter pipe with a splash plate on the bottom to convey water to the pit and reduce side wall erosion or excessive disturbance of the pond bottom. Excessive erosion and bottom disturbance will result in clogging of the infiltration receptor and yield lower than actual infiltration rates.

6. Add water to the pit at a rate that will maintain a water level between 6 and 12 inches above the bottom of the pit. A rotameter can be used to measure the flow rate into the pit.

   Note: For infiltration facilities serving large drainage areas, designs with multiple feet of standing water can have infiltration tests with greater than 1 foot of standing water. The depth must not exceed the proposed maximum depth of water expected in the completed facility.

7. Every 15 to 30 minutes, record the cumulative volume and instantaneous flow rate in gallons per minute necessary to maintain the water level at the same point on the measuring rod.

8. Keep adding water to the pit until 1 hour after the flow rate into the pit has stabilized (constant flow rate; a goal of 5 percent variation or less variation in the total flow) while maintaining the same pond water level. **The total of the pre-soak time plus 1 hour after the flow rate has stabilized should be no less than 6 hours.**

9. After the flow rate has stabilized for at least 1 hour, turn off the water and record the rate of infiltration (the drop rate of the standing water) in inches per hour from the measuring rod data, until the pit is empty. Consider running this falling head phase of the test several times to estimate the dependency of infiltration rate with head.

10. Within 24 hours after the conclusion of testing, over-excavate the pit to see if the test water is mounded on shallow restrictive layers or if it has continued to flow deep into the subsurface. The depth of excavation varies depending on soil type and depth to hydraulic restricting layer, and is determined by the engineer or certified soils professional. Mounding is an indication that a mounding analysis is necessary.

Data Analysis:

1. Calculate and record the infiltration rate in inches per hour in 30 minutes or 1-hour increments until 1 hour after the flow has stabilized.

   Note: Use statistical/trend analysis to obtain the hourly flow rate when the flow stabilizes. This would be the lowest hourly flow rate.

2. To compute the design infiltration rate ($Ksat_{design}$), apply appropriate correction factors outlined previously.

Example:

The area of the bottom of the test pit is 8.5 feet by 11.5 feet.

Water flow rate was measured and recorded at intervals ranging from 15 to 30 minutes throughout the test. Between 400 minutes and 1,000 minutes, the flow rate stabilized between 10 and 12.5 gallons per minute or 600 to 750 gallons per hour, or an average of (9.8 + 12.3) / 2 = 11.1 inches per hour.

To compute the design infiltration rate ($Ksat_{design}$), the infiltration rate must then be adjusted by the appropriate correction factors outlined previously.

B.3.2 Small-Scale Pilot Infiltration Test

A smaller-scale PIT can be used in any of the following instances:

- The drainage area to the infiltration site is less than 1 acre.

- The testing is for bioretention areas or permeable pavement surfaces that either serve small drainage areas and/or are widely dispersed throughout a project site.

- The site has a high infiltration rate, making a large-scale PIT difficult, and the site geotechnical investigation suggests uniform subsurface characteristics.

Infiltration Test:

1. Excavate the test pit to the estimated bottom of the proposed infiltration facility. In the case of bioretention, excavate to the estimated elevation at which the imported soil mix will lie on top of the underlying native soil. For permeable pavement, excavate to the elevation at which the imported subgrade materials, or the pavement itself, will contact the underlying native soil. If the native soils (road subgrade) will have to meet a minimum subgrade compaction requirement, compact the native soil to that requirement prior to testing. Note that the permeable pavement design guidance recommends compaction not exceed 90 to 92 percent. Finally, lay back the slopes sufficiently to avoid caving and erosion during the test. Alternatively, consider shoring the sides of the test pit.

2. The horizontal surface area of the bottom of the test pit should be 12 to 32 square feet. It may be circular or rectangular, but accurately document the size and geometry of the test pit.

3. Install a vertical measuring rod adequate to measure the ponded water depth and that is marked in half-inch increments in the center of the pit bottom.

4. Use a rigid pipe with a splash plate on the bottom to convey water to the pit and reduce side wall erosion or excessive disturbance of the pond bottom. Excessive erosion and bottom disturbance will result in clogging of the infiltration receptor and yield lower than actual infiltration rates. Use a 3-inch-diameter pipe for pits on the smaller end of the recommended surface area, and a 4-inch pipe for pits on the larger end of the recommended surface area.

5. Pre-soak period: Add water to the pit so that there is standing water for at least 6 hours. Maintain the pre-soak water level at least 12 inches above the bottom of the pit.

6. At the end of the pre-soak period, add water to the pit at a rate that will maintain a fixed water level between 6 and 12 inches above the bottom of the pit over a full hour. The depth must not exceed the proposed maximum depth of water expected in the completed facility.

7. Every 15 minutes, record the cumulative volume and instantaneous flow rate in gallons per minute necessary to maintain the water level at the same point (between 6 to 12 inches) on the measuring rod. The specific depth should be the same as the maximum designed ponding depth (usually 6 to 12 inches).

8. After 1 hour, turn off the water and record the rate of infiltration (the drop rate of the standing water) in inches per hour from the measuring rod data, until the pit is empty.

9. A self-logging pressure sensor may also be used to determine water depth and drain-down.

10. Within 24 hours after the conclusion of testing, over-excavate the pit to see if the test water is mounded on shallow restrictive layers or if it has continued to flow deep into the subsurface. The depth of excavation varies depending on soil type and depth to hydraulic restricting layer, and is determined by the engineer or certified soils professional. The soils professional should judge whether a mounding analysis is necessary.

Data Analysis:

Use the guidance for the large-scale PIT method outlined above.

B.3.3 Falling Head Percolation Test Procedure (as modified for the City of Edmonds) (Source: U.S. EPA, On-site Wastewater Treatment and Disposal Systems, 1980)

Note: This test may only be used for performance verification testing, as outlined previously in this appendix. This test may not be used for BMP design, or to demonstrate infeasibility of meeting Minimum Requirement No. 5.

1. Location of Tests

   Tests shall be spaced uniformly throughout the area. If soil conditions are highly variable, more tests may be required.

2. Preparation of Test Hole (as modified for the City of Edmonds)

   The diameter of each test hole is 8 inches, dug or bored to the proposed depths of the absorption systems or to the most limiting soil horizon. To expose a natural soil surface, the bottom of the hole is scratched with a sharp pointed instrument and the loose material is removed from the test hole. A 6-inch-inner-diameter, 4-foot-long, PVC pipe is set into the hole and pressed into the soil 6 inches, and then 2 inches of one-half to three-fourths-inch rock are placed in the pipe to protect the bottom from scouring when water is added.

3. Soaking Period

   The pipe is carefully filled with at least 12 inches of clear water. The depth of water must be maintained for at least 4 hours and preferably overnight if clay soils are present. A funnel with an attached hose or similar device may be used to prevent water from washing down the sides of the hole. Automatic siphons or float valves may be employed to automatically maintain the water level during the soaking period. It is extremely important that the soil be allowed to soak for a sufficiently long period of time to allow the soil to swell if accurate results are to be obtained.

   In sandy soils with little or no clay, soaking is not necessary. If, after filling the pipe twice with 12 inches of water, the water seeps completely away in less than 10 minutes, the test can proceed immediately.

4. Measurement of the Percolation Rate

   Except for sandy soils, percolation rate measurements are made 15 hours, but no more than 30 hours after the soaking period began. The water level is adjusted to 6 inches above the gravel (or 8 inches above the bottom of the hole). At no time during the test is the water level allowed to rise more than 6 inches above the gravel. Immediately after adjustment, the water level is measured from a fixed reference point to the nearest one-sixteenth inch at 30 minute intervals. The test is continued until two successive water level drops do not vary by more than one-sixteenth inch within a 90-minute period. At least three measurements are to be made.

   After each measurement, the water level is readjusted to the 6-inch level. The last water level drop is used to calculate the percolation rate.

   In sandy soils or soils in which the first 6 inches of water added after the soaking period seeps away in less than 30 minutes, water level measurements are made at 10 minute intervals for a 1-hour period. The last water level drop is used to calculate the percolation rate.

5. Calculation of the Percolation Rate

   The percolation rate is calculated for each test site by dividing the time interval used between measurements by the magnitude of the last water level drop. This calculation results in a percolation rate in terms of minutes/inch. To determine the percolation rate for the area, the rates obtained from each hole are averaged. (If tests in the area vary by more than 20 minutes/inch, variations in soil type are indicated. Under these circumstances, percolation rates should not be averaged.) **To compute the design infiltration rate (Ksatdesign), the final percolation rates must then be adjusted by the appropriate correction factors outlined previously**.

   Example: If the last measured drop in water level after 30 minutes is five-eighths-inch, then:

   percolation rate = (30 minutes)/(5/8 inch) = 48 minutes/inch. (At a minimum, a correction factor "CFT" of 0.4 shall be applied to all field methods for determining infiltration rates.)

B.4 Method 2 – Soil Grain Size Analysis Method

For infiltration basins and trenches, for each defined layer below the infiltration facility to a depth below the facility bottom of 2.5 times the maximum depth of water in the facility, but not less than 10 feet, estimate the initial saturated hydraulic conductivity (K_{sat}) in cm/sec using the following relationship (see Massman 2003). For large infiltration facilities serving drainage areas of 10 acres or more, soil grain size analyses should be performed on layers up to 50 feet deep (or no more than 10 feet below the water table).

(Equation 1):

$$\log_{10}(K_{sat}) = -1.57 + 1.90D_{10} + 0.015D_{60} - 0.013D_{90} - 2.08\mathrm{f}_{\mathrm{fines}}$$

Where, D_{10}, $D_{60,}$ and D_{90} are the grain sizes in mm for which 10 percent, 60 percent, and 90 percent of the sample is more fine and f_{fines} is the fraction of the soil (by weight) that passes the U.S. #200 sieve (K_{sat} is in cm/s).

For bioretention areas, analyze each defined layer below the top of the final bioretention area subgrade to a depth of at least 3 times the maximum ponding depth, but not less than 3 feet (1 meter). For permeable pavement, analyze for each defined layer below the top of the final subgrade to a depth of at least 3 times the maximum ponding depth within the base (reservoir) course, but not less than 3 feet (1 meter).

If the licensed professional conducting the investigation determines that deeper layers will influence the rate of infiltration for the facility, soil layers at greater depths must be considered when assessing the site's hydraulic conductivity characteristics. Massman (2003) indicates that where the water table is deep, soil or rock strata up to 100 feet below an infiltration facility can influence the rate of infiltration. Note that only the layers near and above the water table or low permeability zone (e.g., a clay, dense glacial till, or rock layer) need to be considered, as the layers below the groundwater table or low permeability zone do not significantly influence the rate of infiltration. Also note that this equation for estimating Ksat assumes minimal compaction consistent with the use of tracked (i.e., low to moderate ground pressure) excavation equipment.

If the soil layer being characterized has been exposed to heavy compaction (e.g., due to heavy equipment with narrow tracks, narrow tires, or large lugged, high pressure tires) the hydraulic conductivity for the layer could be approximately an order of magnitude less than what would be estimated based on grain size characteristics alone (Pitt 2003). In such cases, compaction effects must be taken into account when estimating hydraulic conductivity.

For clean, uniformly graded sands and gravels, the reduction in Ksat due to compaction will be much less than an order of magnitude. For well-graded sands and gravels with moderate to high silt content, the reduction in Ksat will be close to an order of magnitude. For soils that contain clay, the reduction in Ksat could be greater than an order of magnitude.

If greater certainty is desired, the in-situ saturated conductivity of a specific layer can be obtained through the use of a PIT. Note that these field tests generally provide a Ksat combined with a hydraulic gradient. In some of these tests, the hydraulic gradient may be close to 1.0; therefore, in effect, the test infiltration rate result is the same as the hydraulic conductivity. In other cases, the hydraulic gradient may be close to the gradient that is likely to occur in the full-scale infiltration facility. The hydraulic gradient will need to be evaluated on a case-by-case basis when interpreting the results of field tests. It is important to recognize that the gradient in the test may not be the same as the gradient likely to occur in the full-scale infiltration facility in the long-term (i.e., when groundwater mounding is fully developed).

Once the Ksat for each layer has been identified, determine the effective average Ksat below the pond. Ksat estimates from different layers can be combined using the harmonic mean:

(Equation 2):

$$K_{equiv} = \frac{d}{\sum \frac{d_i}{K_i}}$$

Where, d is the total depth of the soil column, d_i is the thickness of layer "i" in the soil column, and K_i is the saturated hydraulic conductivity of layer "i" in the soil column. The depth of the soil column, d, typically would include all layers between the pond bottom and the water table. However, for sites with very deep water tables (>100 feet) where groundwater mounding to the base of the pond is not likely to occur, it is recommended that the total depth of the soil column in Equation 2 be limited to approximately 20 times the depth of pond, but not more than 50 feet. This is to ensure that the most important and relevant layers are included in the hydraulic conductivity calculations. Deep layers that are not likely to affect the infiltration rate near the pond bottom need not be included in Equation 2.

Equation 2 may over-estimate the effective Ksat value at sites with low conductivity layers immediately beneath the infiltration basin. For sites where the lowest conductivity layer is within 5 feet of the base of the pond, it is suggested that this lowest Ksat value be used as the equivalent hydraulic conductivity rather than the value from Equation 2. Using the layer with the lowest Ksat is advised for designing bioretention areas or permeable pavement surfaces. The harmonic mean given by Equation 2 is the appropriate effective hydraulic conductivity for flow that is perpendicular to stratigraphic layers, and will produce conservative results when flow has a significant horizontal component such as could occur due to groundwater mounding.