Infiltration Testing

Maria Cahill, Green Girl Land Development Solutions; Derek C. Godwin and Marissa Sowles, Oregon Sea Grant Extension

Infiltration tests estimate the rate at which runoff will pass through the native soil from low impact development (LID) infiltration facilities. Any LID facility planned for infiltration should test the soil. These LID facilities might include rain gardens, vegetated filter strips, porous pavements, infiltration planters, swales, drywells, and soakage trenches. The infiltration rate is used to determine whether a site is suitable for surface infiltration facilities, to confirm that water quality standards will be met (that is, the infiltration rate does not exceed 12 inches/hour), and to size the facility to infiltrate the desired design storm (PSP 2009).

A soils map is a good place to start with early planning.

Adapted from USDA Web Soil Survey

Existing soil or geologic maps can be used in the initial steps to evaluate a site's potential for infiltration, but should never be used alone. Ground truthing with infiltration tests very often reveals different conditions in different places on a site at different depths. Several tests are used by various agencies to determine infiltration rates to various degrees of accuracy. Appropriate tests can also vary by the size of area contributing runoff to the LID facility and the type of facility (PSAT 2005). In general, however, each test involves digging a hole at the approximate location and depth of the proposed infiltration facility, pouring water in an open-bottomed ring or dug hole, and measuring the drop over time from the top, which will result in a tested infiltration rate measured in inches per hour.

Filtration facilities, such as filtration rain gardens and filtration planters, allow the runoff to pass through only the upper layers of soil to an underground perforated pipe that routes the water off-site. These facilities don't need infiltration testing of the native soil, but will need to perform infiltration-rate lab testing on the installed amended planting soil to ensure that the entire volume of the water-quality design storm can pass through the soil to the perforated pipe below.

Timing and Location

Tests should "not be conducted in the rain, within 24 hours of significant rainfall events (> 0.5 inches), or when the temperature is below freezing" (SEMCOG 2008). The tests proposed here measure infiltration of a very small and specific area. If the proposed facility has a large area, multiple measurements within the area are suggested to properly assess the site's suitability (PSAT 2005).

Infiltration tests should be performed across the proposed development area prior to full build-out of sites. This provides the opportunity to install LID facilities on optimal soils and geology. If buildings are proposed on high-infiltration soils

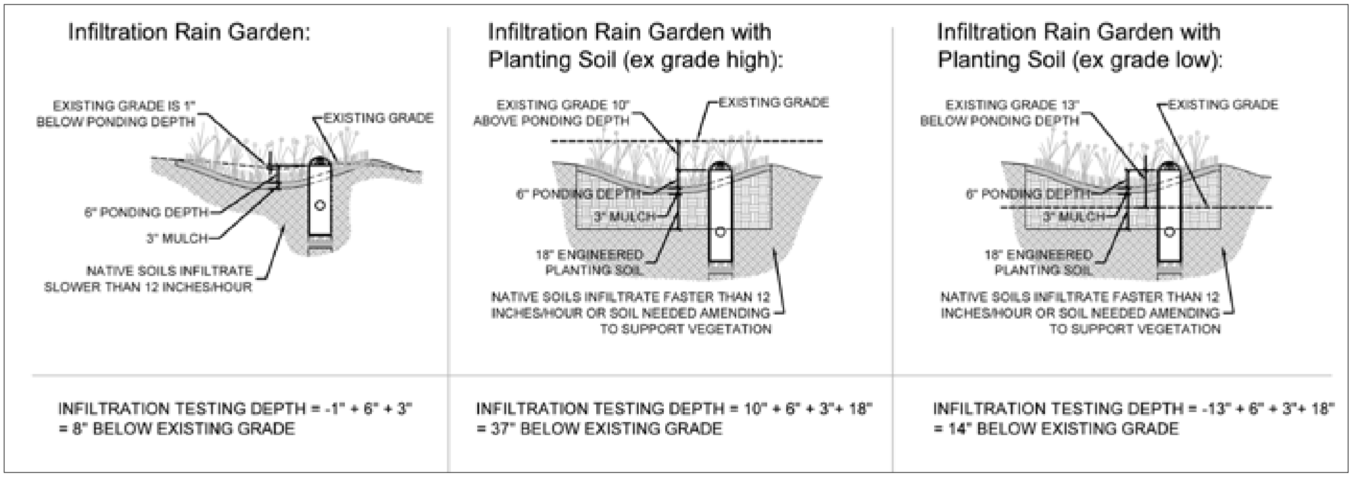
LOW IMPACT DEVELOPMENT

FACT SHEET

Oregon Sea Grant
Corvallis, Oregon

ORESU-G-11-008

Maria Cahill



Infiltration testing depth will vary with type of facility and other siting considerations.

and facilities proposed in lower-infiltrating soils, plans can be modified to improve stormwater management, prevent flooding, address water quality issues, and decrease the cost of the on-site stormwater management facilities. The earlier in the site-development process infiltration tests are conducted, the better. Infiltration information ultimately will be needed to select and design LID facilities.

Testing Depth

Infiltration testing should be performed at the expected depth of the bottom of the facility, but it is important to consider the possibility that infiltration testing will determine the depth of the facility as well as the location. Soils just 6 inches below existing grade may be suitable for infiltration and have enough nutrients to support plant growth. In this case, a very simple facility that doesn't replace the native soils should be considered by testing the soils at a shallow depth. Existing grades will also help determine appropriate testing depths.

Deep drywells, where the bottom and sides of the facility would be too costly to access safely, pose a special challenge for infiltration testing. Because drywells are vertical in nature, they are more likely to pass through two or more different soil horizons. Often they are chosen because surface-soil infiltration rates are poor, but a better-draining soil exists some feet below or because the site surface area is limited. Drywells take up very little space compared to surface infiltration facilities. More discussion about drywell testing follows.

Who Performs Testing

Testing and evaluation is often done by qualified professionals and technicians, including soil scientists, local health-department sanitarians, design engineers, and professional geologists. The City of Portland specifies "a Professional Engineer (PE), Registered Geologist (RG), or Certified Engineering Geologist (CEG) licensed in the State of Oregon" (BES 2008), although in Oregon, training sessions are available for homeowners and master gardeners wishing to install small residential facilities, such as rain gardens. Those professionals involved with site development, especially stormwater infrastructure and facilities, would benefit from observation of these testing procedures to fully understand site characteristics and appropriately plan the site (SEMCOG 2008).

Safety Measures

Infiltration tests require extensive excavation and can be dangerous. All relevant Occupational Safety and Health Administration (OSHA) regulations should be observed. "Excavation should never be left unsecured and unmarked, and all applicable authorities should be notified prior to any work" (SEMCOG 2008). *Check your local jurisdiction for additional requirements.*

Process

The infiltration testing process includes four steps: (1) background evaluation, (2) test pit observations, (3) infiltration testing, and (4) design considerations (SEMCOG 2008). In step 1, the site is evaluated from published data, such as soil and geological maps. One excellent online resource for soils is the Natural Resources Conservation Service's *Web Soil Survey* (NRCS 2009). In addition, unique resources such as riparian areas, steep slopes and other erodible soils, rare geological outcrops (like serpentine), and historic or cultural resources should also be mapped and avoided to the greatest extent possible. *See the site planning checklist provided on the SWAMP Web site* (Cal/EPA 2010). This step may involve a number of professionals, such as a wildlife and wetland scientist, surveyor, arborist, or geotechnical engineer.

In step 2, the test pit is dug, and subsurface conditions such as soil texture, soil horizon depths, fragipan, and bedrock are recorded. In many cases, barriers to siting LID facilities are identified in this step. In step 3, the actual infiltration test to determine soil infiltration rates is performed. In step 4, all collected information is used to select, site, and size facilities in the development area. For more information on steps 1 and 4, see SEMCOG's *Low Impact Development Manual* (2008).

It's possible that additional infiltration testing will be needed after step 4, because the designer may want to relocate a facility from a poorly infiltrating area to an area with better infiltration. The number of infiltration tests for large sites varies widely with jurisdictional requirements, but is also impacted by the uniformity or lack of uniformity in soil conditions across the site. In urban sites, where soils may have been disturbed a number of times over many years, soil conditions may vary greatly over small distances. In any case, it's ideal to test directly over or within close proximity of the proposed facility.


Maria Cahill

The "worm test" is a simple field test to quickly assess the degree to which a soil is clayey. The longer the worm, the greater the concentration of clay particles.

Establishing a Presoaking Duration

In all of the field tests below, presoaking the soil by adding water to the test pit before measuring is one of the recommended steps, but choice of LID facility and environmental conditions make it difficult to choose an appropriate presoaking duration. Infiltration rates vary with the moisture content of the soil. Water added to dry soils will be absorbed and conveyed through the soil column faster than water added to already wet soils. In some regions of the country, presoaking is done simply because it was required by the EPA on all percolation testing done for wastewater systems. This was to simulate the constantly wet conditions that a septic field receiving regular wastewater flows would have to absorb. In eastern Oregon, presoaking may not be needed at all.

In western Oregon, presoaking a test hole should be done to simulate an LID facility in a soil that has already received rainfall and is already wet. No one knows for sure how much presoaking is needed to simulate soil infiltration rates during the wettest month of the year; thus, numerous values are suggested in the literature. Soil type may also impact the length of presoaking time. *Consult your geotechnical engineer or soil scientist for site-specific recommendations.*

Types of Tests

Percolation, modified percolation, and double-ring infiltrometer are three types of field tests used to determine infiltration rates; they are described below. In addition, a laboratory method that relates sieve analysis results to an infiltration rate is discussed.

The Washington State Department of Ecology (WSDOE) recommends the more extensive Pilot Infiltration Test (PIT), when possible, because it provides the most accurate estimate of infiltration. The test is very rarely used because it can take up to 17 hours to complete and requires a lot of water. More information on the pilot infiltration test can be found in the *Stormwater Management Manual for Western Washington* (WSDOE 2005).

According to the WSDOE, both the double-ring infiltrometer test and percolation test overestimate infiltration rates (2005). Additionally, the double-ring infiltrometer is an expensive piece of equipment and is

Summary Comparison Table of the Portland Method and the Reduction Factor Method Percolation Tests

	Portland Method	***Reduction Factor Method***
Site preparation	Excavate a 2' x 2' hole to the elevation of the bottom of the proposed facility.	Excavate as needed to within 6–10" of the bottom of the proposed facility. Dig a hole 6–10" in diameter the remaining depth to the proposed bottom of the facility.
Presoaking	Clay: Presoak overnight by maintaining at least 12" of water.	Presoak 1 hour by maintaining 6" of water for half an hour. Don't add water for the last half hour. Testing can be done right away.
	Sand: If presoaking water seeps away within 10 minutes twice, no presoaking is needed and testing can be done right away.	
	All other soils: Presoak 4 hours minimum by maintaining at least 12" of water.	
Establish testing interval	Fast draining soils: 10-minute intervals for 1 hour	At the end of presoaking, use a 10-minute interval if pit has no water or a 30-minute interval if pit still has water.
	Slow draining soils: 20-minute intervals for two hours	
Testing: measuring the drop in water [inches] over time [minutes]	Refill the hole to a depth of 12". Measure and record the drop in water for the established testing interval, either 10 or 20 minutes until all the water has drained. Refill and allow to empty as needed to test for the appropriate length of time (either 1 or 2 hours). This is one trial. Rerun the trial until the difference in field infiltration rate is minimal, or run a minimum of three trials.	Refill the hole using a depth equivalent to the ponding depth of the facility or a minimum of 6". Measure and record the drop in water for the established testing interval, either 10 or 30 minutes. After each reading, refill the pit and restart the timer. After 8 readings or when the water stabilizes, stop measuring.
Calculate the field infiltration rate [inches/hour]	Average the measurements taken during the last trial.	Average the measurements taken during the stabilized period.
Find safety factor	Safety factor = 2 for this method	Calculate based on the Reduction Factor, Rf equation.
Calculate the design infiltration rate [inches/hour]	Divide the field infiltration rate by 2.	Divide the field infiltration rate by the Reduction Factor.

generally used only by geotechnical professionals (M. Cahill, personal communication, April 13, 2009), but a version made from parts found at a hardware store can be made to simulate the tool.

The following tests yield a tested infiltration rate in inches per minute. Don't forget to convert to inches per hour, which is the industry standard for modeling and designing. Also, depending on site conditions, expected levels of maintenance, and the type of facility, a factor of safety or correction factor (often represented as FS or CF) should be applied to the tested infiltration rate to arrive at a design infiltration rate with a lower value than the tested infiltration rate. In some cases, designers choose not to use a factor of safety at all. *Consult your geotechnical engineer or designer as well as your local jurisdictional engineering department to establish appropriate design infiltration rates for your project.*

PERCOLATION TESTS

A percolation test allows water to infiltrate vertically and laterally, correcting the final infiltration rate with an adjustment factor. This test is generally applicable to any surface infiltration facility, but is used by some consultants for drywells in soils where a modified percolation test (discussed below) isn't feasible.

Open-pit, falling-head procedures

Two methods are described here side by side for comparison, referred to here as the Portland method and the Reduction Factor method. Additional detail for each test follows.

PORTLAND METHOD PERCOLATION TEST

The following section has been adapted and reprinted with permission from the Appendix F2 of the City of Portland Bureau of Environmental Services *Stormwater Management Manual* (BES 2008).

The open-pit, falling-head procedure is based on the Environmental Protection Agency (EPA) Falling Head Percolation Test Procedure (EPA 1980). The test is performed in an open excavation and is a test of the combination of vertical and lateral infiltration.

Site preparation

Excavate an approximately 2-foot by 2-foot hole into the native soil to the elevation of the proposed facility bottom. The test can be conducted in a machine-excavated pit or a pit dug by hand using a shovel, posthole digger, or hand auger. If a smooth auger tool or a smooth excavation bucket is used, scratch the sides and bottom of the hole with a sharp-pointed instrument and remove the loose material from the bottom of the test hole. A 2-inch layer of coarse sand or fine gravel may be placed to protect the bottom from scour and sloughing, which can artificially reduce the tested infiltration rate.

Presoaking

Fill the hole with clean water to a minimum of 1 foot above the soil to be tested, and maintain this depth of water for at least 4 hours (or overnight if clay soils are present) to presoak the native material. In sandy soils with little or no clay, soaking is unnecessary. If, after filling the hole twice with 12 inches of water, the water seeps completely away in less than 10 minutes, the test can proceed immediately.

Testing

Determine how the water level will be accurately measured. The measurements should be made with reference to a fixed point. A lath placed in the test pit prior to filling, or a sturdy beam placed across the top of the pit, are convenient reference points. The tester and excavator should conduct all testing in accordance with OSHA regulations.

After the presaturation period, refill the hole with water to 12 inches above the soil and record the time. Alternative water head heights may be used for testing, provided that the presaturation height is adjusted accordingly and the water head height used in infiltration testing is 50 percent or less than the water head height in the proposed stormwater system during the design storm event. Measure the water level to the nearest 0.01 foot (⅛ inch) at 10-minute intervals for a total period of 1 hour (or, in slower soils, 20-minute intervals for 2 hours), or until all the water has drained. In faster-draining soils (sands and gravels), it may be necessary to shorten the measurement interval to obtain a well-defined infiltration rate curve. Constant-head tests may be substituted for falling-head tests, at the discretion of the professional overseeing the infiltration testing.

Repeat the test. Successive trials should be run until the percent change in measured infiltration rate between two successive trials is minimal. The trial should be discounted if the infiltration rate between successive trials increases. At least three trials must be conducted. After each trial, the water level is readjusted to the 12-inch level. Enter results into a data table.

Design infiltration rate

The average infiltration rate over the last trial should be used to calculate the unfactored infiltration rate. Alternatively, the infiltration rate measured over the range of water head applicable to the project stormwater system design may be used at the discretion of the professional overseeing the testing. The final rate must be reported in inches per hour.

For very rapidly draining soils, it may not be possible to maintain a water head above the bottom of the test pit. If the infiltration rate meets or exceeds the flow of water into the test pit, conduct the test in the following manner:

1. Approximate the area over which the water is infiltrating.
2. Using a water meter, bucket, or other device, measure the rate of water discharging into the test pit.
3. Calculate the infiltration rate by dividing the rate of discharge (cubic inches per hour) by the area over which it is infiltrating (square inches).

Upon completion of the testing, the excavation must be backfilled.

REDUCTION FACTOR METHOD PERCOLATION TEST

Site preparation

In an area in or near the proposed stormwater facility, excavate evenly a hole 6 to 10 inches in diameter to the elevation of the bottom of the proposed facility, typically 8 to 12 inches deep (SEMCOG 2008). This is most easily done with a post-hole digger. Measure and record this diameter for final calculations. Because the digging process tends to consolidate the sides of the hole, and also because this testing procedure readjusts the infiltration rate to account for water flows through the sides of the facility, the soil surfaces (bottom and sides) should be scratched with a sharp tool (BES 2008). Excavation can be done by hand or with machinery. Excess soils resulting from scratching the soil should be removed (SEMCOG 2008). Water added during the test can also cause scouring and pore clogging. To avoid this, "2 inches of coarse sand or fine gravel may be placed in the bottom of the hole" (SEMCOG 2008).

Presoaking

Before beginning the infiltration test, the test area must be presoaked for an hour and a measurement interval time established. Measure at least 6 inches above the native soil surface in the pit and mark this level with a marker such as a nail, stake, or pencil. To presoak the area, fill the hole with water to the marker level. Fill the hole as needed to maintain the approximately 6-inch water depth for 30 minutes (SEMCOG 2008).

Reduction Factor Design Infiltration Rate

The field infiltration rate (referred to below as the "Percolation Rate") is determined by averaging the measurements taken during the stabilized rate period, expressed in inches per hour (SEMCOG 2008).

To correct for horizontal water infiltration, use the following equation:

Design Infiltration Rate = (Percolation Rate)/(Reduction Factor)

where:

Percolation Rate is calculated from the measurements taken during the stabilized rate period.

The Reduction Factor (Rf) = ((2d1 - Δd)/(DIA)) + 1

where:

d1 = Initial Water Depth (in)
Δd = Percolation Rate (average water level drop) (in)
DIA = Diameter of the Percolation Hole (in)

The reduction factor will vary depending on hole size. "Wider and shallower tests have lower reduction factors because proportionately less water is exfiltrated[1] through the sides" (SEMCOG 2008). The percolation test assumes that there is uniform soil across the surface of the pit and water depth affects the percolation rate. If these assumptions are not true for your site, consider using additional adjustments (SEMCOG 2008).

1 Exfiltration "refers to a loss of water from a drainage system as the result of percolation or absorption into the surrounding soil," and is basically just another way of thinking about the infiltration process. Comment taken from the HydroCAD (stormwater modeling software) Web site at http://www.hydrocad.net/exfilt.htm

Maria Cahill

A shovel was used to dig most of the way, then a 6-inch-diameter post-hole digger was used to reach the proposed bottom elevation of a rain garden. Measure the drop in water from a known, stable marker.

Maria Cahill

Add water carefully so that the hole doesn't cave or the sides and bottom don't erode. In clay soils, the clay can re-sort to clog the bottom and give artificially low infiltration rates.

Do not add water in the last 30 minutes of the soaking hour. If the pit contains no water after the 30 minutes, use a 10-minute measurement interval for testing. If water remains in the pit, use a 30-minute interval (SEMCOG 2008). In Oregon, where soil is a mixture of clay and sand, the clay particles can easily be suspended in the presoaking water and clog "or cement up" the sides of the facility. These soils may also cave, and indicate that another location on-site should be investigated, since these soils will likely fail in the same way once an infiltration facility is built over them.

Testing

Refill the hole to the marked water depth, which should approximately equal the expected ponding depth of the proposed facility—at least 6 inches. Filling to a water depth that exceeds the proposed ponding depth will skew the results, because pressure due to the additional depth of water (or "head") will increase the infiltration rate. Using the established interval times and from a fixed reference, measure and record the water-level drop. After each recording, stop the timer, refill the pit to the marker level, and restart the timer. When eight readings have been collected or when the water level drop stabilizes (that is, when the highest and lowest measurements within four consecutive readings are no more than a ¼-inch difference), no more measurements are required (SEMCOG 2008).

MODIFIED PERCOLATION TESTING

An alternate method to the open-hole percolation testing is often used. Instead of an open hole, a 6-inch solid pipe is driven into native soils until it is properly seated to form a seal. Presoaking and testing guidelines should be performed as discussed above, but in this case, water is infiltrating only out the bottom of the pipe and no reduction factor is needed to adjust for hole depth and diameter. A factor of safety for other variables still may be recommended by the geotechnical engineer or soil scientist.

Testing deep soils for drywells

Drywells are good candidates for the modified percolation-testing method. After excavating the first few feet, a deeper hole can then be hand-augured, machine-drilled, or backhoed with a clamshell to the proposed bottom of the drywell. Once excavation is complete, a solid pipe can be seated and used for testing. Since the drywell is a vertical facility, pressure head (due to the depth of water that accumulates in the drywell and pushes water out the sides) plays a more prominent role in dictating infiltration rates than for other facilities. Some consultants choose to test conservatively by using floats to maintain no more than 12 inches of water; others use a depth of water that is convenient for them to test while they stand at the surface, but that depth should never exceed the depth of water that will actually be accumulating in the drywell during large storms.

DOUBLE-RING INFILTROMETER TEST

In this test, the vertical infiltration rate is isolated. Since water moves out through the sides of a facility as fast as through the bottom in most cases, this test is good for facilities that primarily will be infiltrating through its bottom like rain gardens. It may, however, underestimate infiltration rates from facilities like soakage trenches and drywells. An inner ring is used to measure water drop over time; an outer ring minimizes lateral water movement from the inner ring. The test can be performed at different depths, but the rings must penetrate at least 2 inches below the ground's surface. At least 6 inches of both cylinders must be above the surface; therefore, a cylinder should be a minimum of 8 inches high. If the proposed infiltration facility will pond water to a depth greater than 6 inches, taller rings will be needed to simulate the design head. Test kits can be purchased or fashioned with supplies found at most hardware stores (SEMCOG 2008). The double-ring infiltrometer test measures the infiltration rate of a very small and specific area, so if the proposed BMP has a large area, multiple measurements within the the area are suggested to properly assess the site's suitability (PSAT 2005).

Alder Geotechnical

Double-ring infiltrometer with optional measuring beakers.

Supplies

- Two impermeable cylinders (the inner ring should be no smaller than 4 inches in diameter and equal 50 to 70% of the outer ring diameter; for example, use an 8-inch inner ring with a 12-inch outer ring)
- Water source
- Timer
- Measuring device (ruler, measuring tape)
- Flat wooden board that covers diameter of cylinders to push the cylinders into the ground
- Rubber mallet
- Log sheets and writing utensil or computer (SEMCOG 2008)

The City of Portland requires the double-ring infiltrometer test follow ASTM 3385-94 standards (BES 2008), but many municipalities require modified versions of ASTM, which are often less time-consuming. Basic steps are described below, but check with your local jurisdiction for appropriate procedure steps for your area.

Site preparation

In an area in or near the proposed BMP area, excavate to the depth of the bottom of the proposed facility.

Drive the larger outer ring in evenly, at least 2 inches (can be more, but make sure at least 6 inches of the cylinder is above ground) into the ground by setting the flat wooden board atop the cylinder and firmly striking it with the rubber mallet (SEMCOG 2008).

Center the inner ring within the outer ring and follow the same procedure as above with the wooden board and mallet. Make sure the bottoms of both rings (underground) are at the same depth (SEMCOG 2008). Different depths or strata can be tested by excavating a pit area, but make sure the rings are easily accessible and that water can easily be added over a period of hours (BES 2008).

Presoaking

Before beginning the infiltration test, the test area must be presoaked and a measurement interval time established. To presoak the area, fill the inner and outer ring to the brim or water level mark with water. Keep the water level above 4 inches for 30 minutes. At the end of 30 minutes, refill the rings completely.

Measure the water depth in the inner ring and wait another 30 minutes and then measure the water depth again to determine the drop in water level. If the drop is equal to or greater than 2 inches, use 10-minute intervals; if less than 2 inches, use a 30-minute interval (SEMCOG 2008).

Testing

Fill the rings to the brim or water level. Using the established interval times and from a fixed reference, measure and record the water level drop in the inner ring at each interval. After each recording, stop the timer, refill the rings and restart the timer. When eight readings have been collected or the water-level drop stabilizes (when the highest and lowest measurement within four consecutive readings is no more than a ¼-inch difference) no more measurements are required (SEMCOG 2008).

Design infiltration rate

The infiltration rate of the test area is determined by averaging the measurements taken during the stabilized rate, and should be expressed in inches per hour (SEMCOG 2008).

LABORATORY TESTING

Infiltration rates are directly related to a soil's grain-size distribution, which is the range and percentage of soil particle diameters. Soils with small grains, such as clays and silts, will drain more slowly than soils with large grains, such as sands and gravels. In particular, the percentage of clay, which expands as it soaks up sizable amounts of water, reduces infiltration rates. Silts, which may be the same size as clay, can actually have relatively high infiltration rates. Field testing in pockets of silt in Washington County, Oregon, have yielded results between 20 and 45 inches per hour, while clay and clay silts in other parts of the county infiltrate at ½ inch per hour.

The Washington State Department of Ecology has developed two methods that correlate grain-size distribution to infiltration rates: the "USDA Soil Textural Classification," and "ASTM Gradation Testing at Full Scale Infiltration Facilities." Because the ASTM method has been calibrated to full-scale infiltration testing of existing LID facilities, we will discuss this method briefly here. For more information on both methods, see Volume 3, Hydrologic Analysis and Flow Control Design/BMPs in Stormwater Management in Western Washington (WSDOE 2005).

To determine the infiltration rate of a soil using this method, collect a representative sample (the sample is expected to have the same grain-size distribution as the soil left *in situ*). Different soils may require different volumes of soil to gather a representative sample. Send the sample to a soil testing lab and request an ASTM D422 procedure. The lab will dry the soil and run a series of tests on it, including a sieve analysis to assess the volume of the soil's smallest 10% particles, D_{10}.

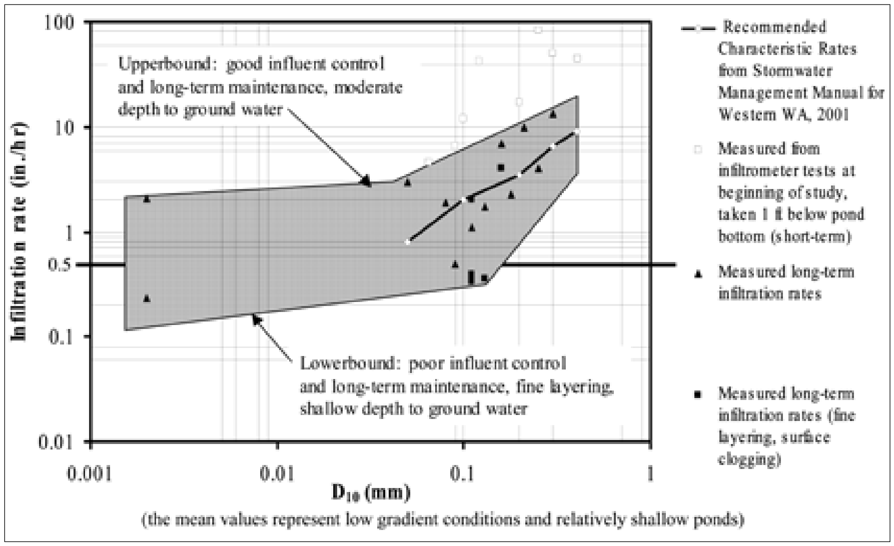
For soils with a D_{10} greater than 0.05 mm, the following table may be used to assign a design (that is, long-term) infiltration rate:

Long-term infiltration rate for soils with D_{10} > 0.05 mm

D_{10} Size from ASTM D422 Soil Gradation test (mm)	Estimated Long-Term (Design) Infiltration Rate (inches/hour)
≥ 0.4	9.0
0.3	6.5
0.2	3.5
0.1	2.0
0.05	0.8

For soils with a D_{10} less than 0.05 mm, the graph below should be used to assign a design (long-term) infiltration rate.

Since these infiltration recommendations represent long-term design infiltration rates and not field-tested infiltration rates, no factor of safety is needed unless there is no pretreatment system for sediments, less-than-average maintenance is expected, or soil horizons are finely layered.



Determine long-term infiltration rates for soils with D_{10} < 0.05 mm. Infiltration Rate as a function of the D_{10} Size of the Soil for Ponds. Source: Stormwater Management for Western Washington, Vol. III, *original Figure 3.28 (WSDOE 2005, pp. 3–78).*

References and Resources

Bureau of Environmental Services (BES). 2008. *Portland Stormwater Management Manual*. City of Portland, Portland, OR. Accessed from http://www.portlandonline.com/bes/index.cfm?c=47952

California Environmental Protection Agency (Cal/EPA). 2010 (last modified). *SWAMP: Surface Water Ambient Monitoring Program* (updated 11/2010). Accessed from http://www.waterboards.ca.gov/water_issues/programs/swamp/

Environmental Protection Agency (EPA). 2002. Falling Head Percolation Test Procedure. *In Onsite Wastewater Treatment and Disposal Systems Design Manual*, EPA/625/1-80-012.

Natural Resource Conservation Service (NRCS). 2009 (last modified). *Web Soil Survey*. USDA Publication. Accessed from http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm

Puget Sound Action Team (PSAT) and Washington State University Pierce County Extension. 2005. *Low Impact Development: Technical Guidance Manual for Puget Sound*. Publication No. PSAT 05-03. Olympia, WA.

Puget Sound Partnership (PSP). 2009. Technical memorandum: Bioretention soil mix review and recommendations for Western Washington. Prepared by Curtis Hinman, Washington State University Extension. Accessed from http://www.psparchives.com/publications/our_work/stormwater/BSMResults-Guidelines%20Final.pdf

Southeast Michigan Council Of Governments (SEMCOG). 2008. *Low Impact Development Manual for Michigan: A Design Guide for Implementers and Reviewers*. Detroit, MI.

Washington State Department of Ecology (WSDOE) Water Quality Program. 2005. Hydrologic Analysis and Flow Control Design/BMPs. *In Stormwater Management Manual for Western Washington, Vol. III*. Pub. No. 05-10-31. Washington Department of Ecology, Olympia, WA.

Washington State Department of Transportation (WSDOT). 2008. *Highway Runoff Manual*. Publication No. M 31-16.01. WSDOT Administrative and Engineering Publications, Olympia, WA.

Washington State Department of Transportation (WSDOT). n.d. Various reports. *Stormwater Research—Reports.* Accessed from http://www.wsdot.wa.gov/Environment/WaterQuality/Research/Reports.htm

Editing and layout by Rick Cooper; template design by Patricia Andersson.

This report was prepared by Oregon Sea Grant under award number NA06OAR4170010 (project number A/ESG-07) from the National Oceanic and Atmospheric Administration's National Sea Grant College Program, U.S. Department of Commerce, and by appropriations made by the Oregon State legislature. The statements, findings, conclusions, and recommendations are those of the authors and do not necessarily reflect the views of these funders.