8.0 INSPECTION AND TESTING PROTOCOLS

8.1 Visual Indicator Protocols

Appendix C describes protocols for assessing each of the twenty-nine (29) visual indicators for inspecting LID BMPs. Visual indicator protocols are organized according to the BMP component that they pertain to. The visual indicators approach allows for a rapid assessment of an LID BMP within a few hours by visually examining the condition of key features in a logical sequence (CSN, 2013). The observed condition for each indicator is recorded on an inspection field data form (Appendix D), documented by photographs and compared to quantitative or qualitative triggers to determine if follow-up tasks are warranted (e.g., routine maintenance, structural repair, further investigation).

Protocols for each visual indicator provide the following information for each relevant BMP type:

- Types of inspections that the indicator is used for;
- BMP component that it relates to;
- Brief description of what to look for or measure;
- Visual examples of passing and failing conditions;
- Conditions that trigger the need for follow-up tasks; and
- Typical follow-up tasks.

These protocols can be used to train inspectors about the visual indicators prior to conducting field visits to help ensure consistency in how the work is done. It is recommended that the components relevant to the BMP under inspection be examined in the order they appear in the following sections since they follow a logical progression that mirrors how water is delivered to and flows through the BMP. Following this sequence will reinforce the inspector's understanding of the function of the BMP while helping to hone in on the cause of any observed issues with its condition or function.

Inspection field data form templates have been provided for each type of LID BMP in Appendix C, and should be used to record observations, measurements and details about the locations where sampling, testing or measurements are undertaken, and follow-up tasks prescribed by the inspector along with timeframes for completing them.

The following equipment may be needed to complete visual indicator assessments:

- Camera;
- Small whiteboard and dry erase marker (to help keep track of what site or component is depicted in photographs);
- Safety apparel (hard hat, steel-toe boots, gloves, eye protection, safety vest);
- Safety cones (for restricting traffic from areas being inspected);
- Clipboard, pen and copies of blank inspection field data forms;

- Copies of as-built drawings and planting plans, BMP inspection and maintenance plan and results from the previous inspection;
- Shovel;
- Hand tools (e.g., screwdrivers, wrenches, pliers);
- Pick (for accessing manholes and catchbasins);
- Multi-gas detector, recently calibrated and bump tested (for entry into manhole/catchbasin/cisterns confined spaces);
- Tripod, winch and harness (for entry into manhole/catchbasin/cisterns confined spaces);
- Flashlight or headlamp;
- Measuring wheel;
- Measuring tape;
- Ruler or metre stick;
- Water level tape (for manual measurements of water level in monitoring wells);
- Stakes, string and hanging level (for estimating maximum ponding depth);
- Waterproof push camera (for inspecting sub-drains and outlet pipes).

8.2 Soil Characterization Testing

The soil component of an LID BMP contributes substantially to its stormwater treatment performance and overall function. If the soil is overly compacted or very finely textured, it may drain too slowly. If the soil is highly organic or contains excessive amounts of chemical fertilizer it may contribute to nutrient loads to receiving waters rather than reduce them. If the soil is too shallow it may not provide adequate treatment of contaminated stormwater or may not support healthy vegetation. Whether it be the engineered filter media of bioretention cells, the growing media of green roofs or the topsoil of enhanced swales, vegetated filter strips and soil amendment areas, it is important that the soil provide a healthy growing environment for plantings while being within design specifications for key parameters specific to the type of BMP.

It is most important to sample and test soil characteristics as a part of Construction and Assumption inspections, to confirm the BMP has been constructed with materials that meet design specifications and that installation of the soil component is acceptable. <u>Testing to confirm that the material meets quality specifications (i.e., particle-size distribution, organic matter, pH, cationic exchange capacity, nutrients and soluble salts) needs to be completed prior to it being delivered to the construction site. Testing to confirm that installation of the soil component is acceptable (i.e., depth and compaction) should be performed after the installed material has been allowed to settle for at least two (2) weeks, and prior to planting</u>.

Sampling and testing is also recommended as a part of Verification inspections, to determine if the BMP is being adequately maintained and if soil characteristics are still within acceptable ranges. It may also be done as part of Forensic inspection and Testing (FIT) work to help diagnose the cause of poor vegetation cover, drainage or treatment performance and decide on corrective actions.

Inspection field data forms provided in Appendix D can be used to record and document the sampling approach and results of tests performed in the field.

Table 8.1 describes the soil characteristics (i.e., parameters and specifications) that are critical to the performance and function of each type of LID BMP containing a soil component and the type of testing involved in determining if the soil is within an acceptable range. <u>For Construction and Assumption inspections, the final design specifications relating to the soil component of the BMP or product specifications from the media supplier should be used as the Acceptance Criteria, which may be different ranges than those in Table 8.1.</u> The values in Table 8.1 represent acceptable ranges for established BMPs (e.g., ones that have been operating for 3 years or more) and should be used during Verification inspections to determine if the BMP is being adequately maintained.

Table 8.1: *Critical soil characteristics, acceptance criteria and tests by LID BMP type.*

LID BMP Type	Soil Characteristic	Acceptance Criteria [1]	Test
Bioretention and Dry Swales (filter media)	Texture [2]	Loamy Sand or Sandy Loam; 70 to 88% sand-sized particles; 12 to 30% silt- and clay-sized particles; <20% clay-sized particles.	Particle-Size Distribution (PSD), or % Sand/Silt/Clay (i.e., Soil Texture) plus Sand Fraction
	Organic Matter (OM)	3 to 10% by dry weight [2]	Walkley-Black method when OM <7.5% or Loss On Ignition (LOI) method when OM ≥7.5% [3]
	Soil pH	6.0 to 7.8	pH of a Saturated Paste [3]
	Cationic Exchange Capacity	>10 meq/100 g	Cationic Exchange Capacity Test
	Phosphorus [4]	12 to 40 ppm	Extractable Phosphorus
	Soluble Salts [5]	≤2.0 mS/cm (0.2 S/m)	Electrical Conductivity of a Soil-Water Slurry (2:1 water to soil ratio by volume) [3]
	Depth	+/- 10% of design specification	Soil Cores, Test Pits or Cone Penetration Tests
	Compaction [6]	Surface Resistance: ≤110 PSI; Sub-surface Resistance: ≤260 PSI Bulk Density: ≤1.60 g/cm^3	Cone Penetration Tests or Bulk Density Tests
	Permeability	i ≥25 mm/h ($K_S \geq 1 \times 10^{-5}$ cm/s); and i ≤203 mm/h ($K_S \leq 0.02$ cm/s).	Surface Infiltration Rate Tests
Enhanced Swales (topsoil)	Texture	Same soil texture classification as specified in the final design or recorded on the as-built drawing	Particle-Size Distribution (PSD), or % Sand/Silt/Clay (i.e., Soil Texture) plus Sand Fraction
	Organic Matter (OM)[2]	5 to 10% by dry weight	Walkley-Black method when OM <7.5% or Loss On Ignition (LOI) method when OM ≥7.5% [3]
	Soil pH	6.0 to 7.8	pH of a Saturated Paste [3]
	Phosphorus [4]	12 to 40 ppm	Extractable Phosphorus
	Soluble Salts [5]	≤2.0 mS/cm (0.2 S/m)	Electrical Conductivity of a Soil-Water Slurry (2:1 water to soil ratio by volume) [3]
	Depth	+/- 10% of design specification	Soil Cores, Test Pits
	Compaction	Surface Resistance: ≤110 PSI; Sub-surface Resistance: Use soil texture class and Table 8.3 to determine maximum acceptable value; Bulk Density: Use PSD to interpolate maximum bulk density value from Figure 8.7.	Cone Penetration Tests or Bulk Density Tests
	Permeability	i ≥15 mm/h ($K_S \geq 1 \times 10^{-6}$ cm/s)	Surface Infiltration Rate Tests

Vegetated Filter Strips and Soil Amendment Areas (topsoil)	Texture	Same soil texture classification as specified in the final design or recorded on the as-built drawing	Particle-Size Distribution (PSD), or % Sand/Silt/Clay (i.e., Soil Texture) plus Sand Fraction
	Organic Matter (OM)	5 to 10% by dry weight [2]	Walkley-Black method when OM <7.5% or Loss On Ignition (LOI) method when OM ≥7.5% [3]
	Soil pH	6.0 to 7.8	pH of a Saturated Paste [3]
	Depth	+/- 10% of design specification	Soil Cores, Test Pits
	Phosphorus [4]	12 to 40 ppm	Extractable Phosphorus
	Soluble Salts [5]	≤2.0 mS/cm (0.2 S/m)	Electrical Conductivity of a Soil-Water Slurry (2:1 water to soil ratio by volume) [3]
	Compaction	Surface Resistance: ≤110 PSI; Sub-surface Resistance: Use soil texture class and Table 8.3 to determine maximum acceptable value; Bulk Density: Use PSD to interpolate maximum bulk density value from Figure 8.7.	Cone Penetration Tests or Bulk Density Tests
	Permeability	i ≥15 mm/h (K_S ≥1 x 10^{-6} cm/s)	Surface Infiltration Rate Tests
Green Roof (growing media)	Texture	See product vendor or BMP designer for specifications	Particle-Size Distribution (PSD), or % Sand/Silt/Clay (i.e., Soil Texture) plus Sand Fraction
	Maximum Media Density	See product vendor or BMP designer for specification	Maximum Media Density Test (ASTM E2399/E2399M-15)
	Water Storage Capacity [7]	Extensive: ≥35% by volume	Part of Maximum Media Density Test (ASTM E2399/E2399M-15)
		Intensive: ≥45% by volume	Part of Maximum Media Density Test (ASTM E2399/E2399M-15)
	Air-Filled Porosity [7]	≥10% by volume	Part of Maximum Media Density Test (ASTM E2399/E2399M-15)
	Permeability, Saturated Media	See product vendor or BMP designer for specification	Part of Maximum Media Density Test (ASTM E2399/E2399M-15)
	Organic Matter (OM)	See product vendor or BMP designer for specification	Walkley-Black method when OM <7.5% or Loss On Ignition (LOI) method when OM ≥7.5% [3]
	Soil pH [8]	6.5 to 7.8	pH of a Saturated Paste
	Soluble Salts [8]	≤0.85 mS/cm (0.085 S/m)	Electrical Conductivity of a Saturated Media Extract (SME) solution
	Phosphorus [9]	2.2 to 40.0 ppm	Extractable Phosphorus of a Saturated Media Extract (SME) solution

Notes:

1. Values represent acceptable ranges for established BMPs (i.e., in operation for 3 years or more). For Construction and Assumption inspections, final design and soil or media product specifications and permissible tolerance ranges should be used as the acceptance criteria, which may be smaller ranges than the values in this table.
2. Suggested range for diagnosing suspected problems with drainage function, vegetation cover or vegetation condition for established BMPs constructed with filter media that meets recommended guidelines (CVC & TRCA, 2010). For proprietary filter media products, different ranges may be acceptable. Product specifications should be provided by the media supplier. Test results should be compared to the media supplier's specifications and permissible tolerance ranges.
3. Based on Ontario Ministry of Food and Rural Affairs' Soil Fertility Handbook guidance on soil fertility testing for crop production (OMAFRA, 2006).
4. Based on Minnesota Pollution Control Agency (MPCA, 2015) for minimum to sustain plant growth and Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA, 2014) for a maximum to avoid unnecessary fertilization that would have low or no effect on plant health.
5. Based on the threshold for non-saline soils (Whitney, 2012).
6. Interpolated value from Figure 8.7 based on a sandy loam soil containing at least 70% sand-sized particles.
7. Based on German green roof standards (FLL 2008). Specifications will vary depending on the green roof growing media product. Product specifications should be provided by the media supplier. Test results should be compared to the media supplier's specifications and permissible tolerance ranges.
8. Based on Penn State University Center for Green Roof Research (Berghage et al. 2008).
9. Based on Penn State University Center for Green Roof Research (Berghage et al. 2008) for the minimum to sustain plant growth and Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA, 2014) for the maximum to avoid unnecessary fertilization that would have low or no effect on plant health.

The following sections describe sampling procedures and acceptable test methods associated with each soil characteristic (i.e., parameter) that should be tested to confirm the soil component of the LID BMP is within an acceptable range.

8.2.1 Soil Sampling Methods and Equipment

The approach to soil sampling will vary depending on what type of inspection is being performed.

As part of a Construction and Assumption inspections, the objective of soil sampling and testing is to confirm that the quality, depth and physical properties of the soil meets design specifications. In Verification inspections, the objectives are to determine if the BMP is being adequately maintained and if the soil properties are still within acceptable ranges for key parameters affecting BMP functional performance. As part of Forensic Investigation and Testing (FIT) work the objective is to help diagnose the cause of potential problems with functional performance detected through visual inspections or other types of testing and decide on appropriate corrective actions. Soil sampling is done to examine how the characteristics of the soil vary over the surface area and depth of the BMP (e.g., has the texture of bioretention filter media at the BMP surface and nearest the inlets become finer than Acceptance Criteria due to accumulation of fine sediment?). So FIT work requires a different approach to sampling that targets problem areas and specific depth ranges and produces multiple samples for laboratory testing.

In general, soil samples should be collected as per ASTM D6640-01 Standard Practice for Collection and Handling of Soils Obtained in Core Barrel Samplers for Environmental Investigations (ASTM International, 2015). Before sampling the soil, any mulch, natural debris (i.e., leaves and branches) and grass cover should be removed from the specific location to be sampled. While collecting samples, it is good practice to make a sketch of the BMP perimeter and sampling locations along with an indicator of orientation (e.g., a north arrow) and rough locations of inlets and outlets. Inspection field data forms provided in chapter 7 should be used to record sample numbers and locations (e.g., sketches) along with other information about the sampling approach (e.g., soil depth range each sample represents).

Equipment needed for soil sampling includes the following:

- Safety apparel (steel toed boots, gloves and eye protection)
- Clipboard, inspection field data forms, pens
- Shovels (e.g., spade and trowl)
- Pails (to contain bulk samples)
- Hand tools (e.g., hammer, screw driver, pliers, wrenches)
- Wooden stakes
- Soil core sampler
- Acrylic soil core sample tubes and caps,
- Plastic bags or containers, sealable
- Duct tape and markers (for sealing and labelling sample containers)
- Ruler or metre stick;
- Measuring tape (and measuring wheel for large BMPs)
- GPS or mobile device

Construction Inspections

The objective of soil sampling and testing as part of Construction inspections is to confirm that the physical and chemical properties of the soil to be used to construct the BMP meets design specifications. For all topsoil or media products to be used to construct LID BMPs, laboratory test results showing that the material meets design or product specifications (i.e., quality control/assurance documentation) should be provided to the designers and construction site supervisor or project manager prior to delivery to the construction site. Samples submitted for laboratory testing should be collected during the beginning, middle and end of the blending process or the top, middle and bottom of the pile. For proprietary media mixtures (e.g., bioretention filter media, green roof growing media) specifications and quality control/assurance documentation should be obtained from the media supplier prior to the material being delivered to the construction site.

After the material has been accepted for delivery and has been installed at the construction site, further sampling and laboratory testing should be done as part of the Assumption inspection to assure the product quality was not compromised during transport or installation (see below for guidance on sampling methods).

Assumption and Verification inspections

For Assumption and Verification inspections, the sampling approach should focus on producing a sample that is representative of the entire soil component of the BMP. To produce such a sample requires collecting material through the full depth of soil in multiple locations distributed evenly across the BMP surface, combining them into a bulk sample, homogenizing the bulk sample and deriving a composite sample from it. For very large BMP footprints (e.g., soil amendments), generating and testing multiple composite samples may be necessary.

Samples are most easily collected using a soil corer (Figure 8.3) to collect cores at approximately 30 cm depth intervals at each location, to the full depth of soil present. Samples can also be obtained by digging a test pit and collecting material from the full depth of the soil layer using a trowl and bucket. For enhanced swale, vegetated filter strip and soil amendment BMPs, soil cores or test pits must extend to the sub-soil layer in order to determine the depth of topsoil present. Topsoil depth can be determined by examining the colour of the soil, with the topsoil layer ending when dark brown coloured soil transitions to lighter coloured subsoil that is low in organic matter (Figures 8.1and 8.2). See section 8.2.2 for further guidance on sampling methods to determine soil depth.

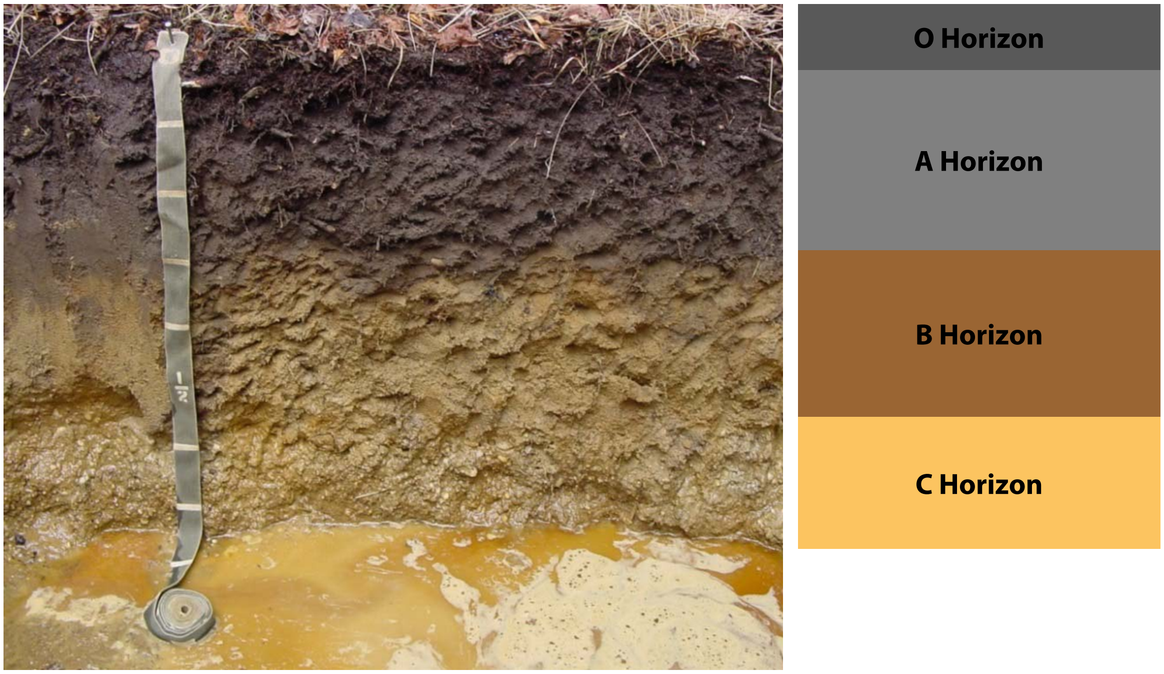
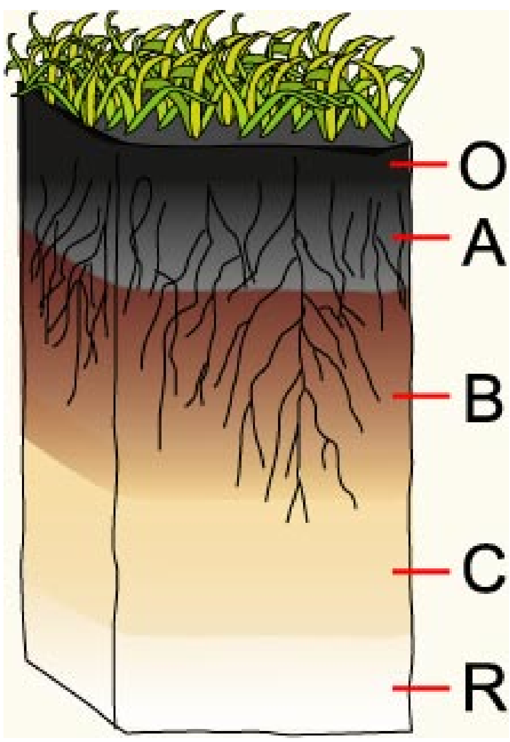


Figure 8.1: *Photograph of a test pit revealing O,A, B and C soil horizons(Source: Mount St. Mary`s University).*



O Horizon – contains organic materials in various stages of decomposition;

A Horizon – surface mineral layer containing some organic material and a mix of clay, sand and gravel, and is usually darker than lower layers;

B Horizon – Mix of clay, iron and aluminum and has lighter colour than the A horizon;

C Horizon – this layer contains partly weather or decomposed rock;

R Horizon – solid rock (bedrock) layer

Figure 8.2: *Schematic of soil horizons (Source: Sydney TAFE).*

For bioretention, enhanced swales and green roofs, samples of the full depth of soil in the BMP should be collected in at least five (5) locations or at a rate of one sample for every twenty-five (25) square metres (m^2) of vegetated BMP area, evenly distributed over the BMP surface, and combined to produce a bulk sample. For vegetated filter strips, soil amendment areas and grassed permeable pavements samples should be collected at a rate of one for every 250 m^2 of vegetated BMP area, evenly distributed over the BMP surface, and combined to produce a bulk sample. The bulk sample should then be stirred to homogenize the material as best as possible. A composite sample should then be derived from the homogenized bulk sample that is of sufficient quantity to allow all applicable laboratory tests to be done. Place at least one litre (L) of the material into a clean, sealable container (e.g., plastic bag or container) to produce the composite sample. Label the sample with the date and identifiers that describe the BMP and submit it to an accredited soil laboratory (see Appendix A for a list of accredited soil testing laboratories in Ontario) for testing of the parameters described in Table 8.1.

If Cone Penetration Tests are the chosen method for evaluating the degree of soil compaction (recommended), refer to section 8.2.3 for guidance on the sampling approach. If Bulk Density is the chosen method of evaluating the degree of compaction, soil core samples from each sampling location must be collected using a soil core sampler (Figure 8.3) and submitted to the laboratory intact, in properly labelled acrylic sample tubes capped on both ends, in addition to the composite sample.

Forensic Investigation and Testing

When potential problems with the drainage, vegetation cover or functional performance of a BMP are suspected based on findings from visual inspection or other types of testing (e.g., surface infiltration rate testing, natural or simulated storm event testing) more detailed soil sampling and testing may be warranted. The objective of soil characterization testing in such cases is to examine how the characteristics of the soil vary over the surface area and depth of the BMP to further diagnose the cause of poor drainage, vegetation cover or condition, or effluent quality, determine what portion of the BMP is in need of structural repair or rehabilitation, and to select the appropriate procedure.

The number and distribution of sampling locations will be determined by the nature of the functional performance problem, but in general, areas to focus on include the following:

- Locations of dead or dying vegetation or highly saturated soil;
- Differences in characteristics between the surface soil layer (e.g., top 15 cm) and deeper layers to determine if accumulation of fine sediment or organic matter on the filter bed surface is impairing the drainage rate, soil fertility or effluent quality.

Figure 8.3: *Images of a simple soil corer, core barrel sampler and acrylic sample tubes .Left: Soil core sampler (Source: Amazon); Centre: Split soil core sampler kit which preserves the soil sample for further testing (i.e., bulk density). (Source: Ereink); Right: Soil Core Sampler (Source: Ereink).*

Separate soil samples of at least 1 L in quantity should be collected for each sampling location and depth interval of interest.

To help diagnose the cause of poor drainage performance detected through visual indicators or other testing (e.g., surface infiltration rate testing, natural or simulated storm event testing) collect separate samples for 0 to 15 cm depth and 15 to 30 cm depth intervals from problem areas, test for particle-size distribution (PSD) and organic matter, and compare to design or product specifications or Acceptance Criteria (Table 8.1). If test results show the surface soil has a finer texture or greater organic matter content than acceptable, procedures to repair/rehabilitate the soil may include core aeration, removal of accumulated sediment and debris, tilling surface sediment, debris and soil to 20 cm depth or greater, or replacement of the surface soil with material that meets specifications.

To help diagnose the cause of poor vegetation cover or condition, collect separate samples for 0 to 15 cm depth and 15 to 30 cm depth intervals from problem areas, test for organic matter, nutrient concentrations and soluble salts, and compare to design or product specifications or Acceptance Criteria (Table 8.1). If test results show the soil is deficient in organic matter or nutrients, it may need to be amended with compost to improve fertility and sustain vegetation cover. If test results show the soil contains an excessive concentration of soluble salts, the problem area should be flushed with fresh water and consideration should be given to selecting plants that are more tolerant to salt.

To help diagnose the cause of poor effluent quality detected through natural or simulated storm event testing and continuous monitoring, collect a composite sample representative of the entire soil component of the BMP using the method described in the previous sub-section and test for Organic Matter, cationic exchange capacity (CEC) and nutrient concentrations, and compare to design or product specifications or Acceptance Criteria (Table 8.1). If the test results show the soil contains higher organic matter or nutrient concentrations or lower CEC than Acceptance Criteria (Table 8.1) or product specifications, repair procedures may include removal of accumulated sediment and debris, incorporation of amendment(s) to increase retention of soluble nutrients or cationic exchange capacity, or replacement with material that meets specifications.

8.2.2 Depth

Soil depth is an important parameter to be confirmed as part of Assumption and Verification inspections as it will affect the vitality of plantings and stormwater treatment performance in terms of water retention and effluent quality. Testing to confirm soil depths are acceptable should be performed after the installed material has been allowed to settle for at least two (2) weeks, and prior to planting. There are three methods that can be used to evaluate soil depth: test pits, soil cores and soil probes (e.g., cone penetrometer). Table 8.2 describes each method and which LID BMPs they are best suited for. It is important to note that using a soil corer to collect core samples results in some compaction of the sample produced, so the media or topsoil depth value measured from the core sample needs to be corrected before using the information to determine if installation of the soil component is acceptable. To correct for compaction of the soil core sample produced through the collection process, divide the value for media or topsoil depth measured from the soil core sample by the compaction correction factor obtained by dividing the total length of the soil core sample by the total depth of the borehole produced through sampling (Equation 8.1).

Equation 8.1: *Soil core sample compaction correction factor.*

$$C = Lc/Db$$

Where,

C = Compaction correction factor

Lc = Length of soil core sample, total

Db = Depth of borehole, total

To evaluate the soil depth for bioretention, dry swales and enhanced swales, measure depths using a method recommended in Table 8.2 in at least five (5) locations or at a rate of one sample for every twenty-five (25) square metres (m^2) of vegetated BMP area, evenly distributed over the BMP surface. For vegetated filter strips, soil amendment areas, permeable pavements with grass cover and green roofs, measurements should be made at a rate of one for every 250 m^2 of vegetated BMP area, evenly distributed over the BMP surface. Measurement locations should be recorded on the field data form, including a plan view sketch of the BMP showing the spatial distribution of measurements.

For a bioretention cell or dry swale with no sub-drain, enhanced swale, vegetated filter strip or soil amendment area, soil cores or test pits must extend to the top of the sub-soil (i.e., B horizon) in order to determine the depth of filter media or topsoil present. Soil depth can be determined by examining the colour of the soil, with the filter media or topsoil layer ending when darker coloured soil transitions to lighter coloured subsoil that is low in, or devoid of dark brown coloured organic matter (Figure 8.1).

To determine if the observed soil depths are acceptable, calculate the mean value and compare to design specifications. <u>If the mean observed soil depth is less than the design specification by 10% or more (see Acceptance Criteria in Table 8.1), corrective actions are needed to address this deficiency</u>. Corrective action involves addition of soil material until an acceptable average depth is achieved which may require regrading.

8.2.3 Compaction

Drainage, water holding capacity and fertility characteristics of a soil can be greatly affected by the degree to which the soil has been compacted. Compaction of soil decreases porosity (i.e., void spaces between soil particles) and increases density which reduces the capacity of the soil to infiltrate and absorb water and can inhibit penetration by the roots of plants at excessive levels. Excessive compaction can result from the soil being subjected to heavy vehicle or foot traffic, storage of heavy materials or mechanical compaction equipment.

An important part of Assumption and Verification inspections includes testing the soil component of LID BMPs to ensure it has not become overly compacted. There are two acceptable approaches to testing soil compaction; Cone Penetration Tests performed by the inspector using a soil cone penetrometer; or Bulk Density tests performed by a soil laboratory on intact core samples. The choice of method will depend on the type of BMP being examined, physical properties of the soil, equipment available to the inspector and turnaround time for receiving test results. The quickest and cheapest method is by performing Cone Penetration Tests on the soil in the field, which is suitable for all types of soil, but requires the use of a soil cone penetrometer that is in good working order and an inspector familiar with its proper use. A more time-consuming and costly, but potentially more accurate method is by collecting intact soil core samples with a Core Barrel Sampler and submitting them for Bulk Density testing by a soil laboratory. Using the Bulk Density method may be problematic for highly coarse, organic or friable soil which, because of their lack of cohesiveness, makes collecting intact core samples difficult. It also involves laboratory testing which typically requires a few weeks to produce test results, which makes it unsuitable for use as part of Construction inspections.

Table 8.2: *Recommended methods for testing soil depth by LID BMP type.*

Method	LID BMP Type Suitability	Description	Equipment Needed
Test pits	Bioretention and Dry Swales; Enhanced Swales Vegetated Filter Strips & Soil Amendment Areas; Green Roofs	1. Dig a small vertical walled excavation that is deep enough to reveal the full depth of topsoil present; 2. Estimate depth of topsoil present; 3. Measure topsoil depth with a ruler or measuring tape.	◖ Shovel ◖ Measuring tape
Soil cores	Bioretention and Dry Swales; Enhanced Swales; Vegetated Filter Strips & Soil Amendment Areas; Green Roofs	1. Collect soil core sample using a soil corer; 2. Measure the total length of the soil core sample (Lc); 3. Measure the length of the soil core sample that is media or topsoil; 4. Measure the total depth of the borehole produced by the corer (Db); 5. Calculate Compaction Factor (C) using Equation 8.1; 6. Divide the length of the soil core sample that is media or topsoil by the Correction Factor to produce the corrected value for media or topsoil depth.	◖ Soil corer ◖ Measuring tape
Soil probes	Bioretention and Dry Swales (with sub-drains)	1. Insert the probe or cone penetrometer into the soil until the sub-drain is reached (when probe cannot be inserted any further); 2. Mark the soil surface level on the probe; 3. Remove probe and measure the depth it reached using a measuring tape.	◖ Probe or soil cone penetrometer at least 1 m in length ◖ Measuring tape

Cone Penetration Test

A common method for evaluating soil compaction is by the Cone Penetration Test (CPT). It is an in-situ test that can be performed in the field by the inspector on all soil types with the results immediately available for use in determining if corrective actions are needed. Cone penetration tests involve measurements of the maximum resistance to pushing an instrument with a conical tip into the soil at a controlled rate (Figure 8.4). The instrument used to take the measurement is called a soil cone penetrometer (ASABE, 2004). Readings depend on cone properties (angle and size) and soil properties (e.g., bulk density, texture, and soil moisture) (ASAE,1999; Herrick and Jones, 2002). As cone penetrometer readings are strongly related to soil moisture, measurements should be taken within a day or two after a heavy rainfall event or when soils are at, or near field capacity (i.e., fully wetted but not saturated).

There are two general types of cone penetrometers: static penetrometers (Figure 8.5) and dynamic penetrometers (Figure 8.6). The distinction between the two penetrometers lies in how force is applied to the cone.

Static cone penetrometers (Figure 8.5) measure the force required to manually push a metal cone through the soil at a consistent rate. The force is usually measured by a load cell or strain gauge coupled with an analog dial or pressure transducer for readout (ASABE, 2004). As the operator pushes down on the penetrometer, an assistant (for mechanical static soil cone penetrometers) or the instrument itself (for electronic static soil cone penetrometers) records values for each depth increment to evaluate the degree, depth, and thickness of compacted layers. For performing a Cone Penetration Test using a hand-held soil cone penetrometer, the American Society of Agricultural Engineers (ASAE) standards require using a steel cylindrical cone with a 30-degree tip. The diameter of the cone is 20.27 mm for soft soils or 12.83 mm for hard soils (ASABE, 2004). The force is commonly expressed in kilopascals (kPa), or an index of soil strength referred to as the cone index, or as surface resistance in kilograms per square centimetre (kg/cm^2) or pounds per square inch (PSI). The cone should be inserted into the soil at a steady rate of about 3 cm/s (USDA, 2005).

Acceptable procedures for cone penetration testing of soils using static soil cone penetrometers and reporting of the results are provided in the American Society of Agricultural Engineers (ASAE) EP542 Procedures for Using and Reporting Data Obtained with the Soil Cone Penetrometer (ASAE, 1999). Acceptable procedures for cone penetration testing of soil using electronic static cone penetrometers are provided in the instrument operating instructions (e.g., Eijkelkamp Agrisearch Equipment, 2014).

Figure 8.4: *Cone penetration testing with mechanical static, electronic static and dynamic cone penetrometers (Source: DGSI (left) Eijkelkamp (middle), Hoskin Scientific (right)).*

Figure 8.5: *Examples of mechanical static and electronic static soil cone penetrometers. Left: Hand-held static soil cone penetrometer set, mechanical with analog dial display; Right: Hand-held static soil cone penetrometer set, electronic with data logger. (Source: ELE International).*

Dynamic cone penetrometers (Figure 8.6) apply a known amount of kinetic energy to the cone, which causes the penetrometer to move a distance through the soil (Herrick and Jones, 2002). Dynamic penetrometers do not rely on constant penetration velocity, as most use a slide hammer of fixed mass and drop height to apply consistent energy with each blow. Either the number of blows required to penetrate a specified depth, or the depth of penetration per blow are measured. Measurements can be converted into cone index values. Soil resistance for each soil depth interval is calculated using standard equations that account for differences in hammer drop distance, weight, and cone size. Acceptable test methods for cone penetration tests using a dynamic cone penetrometer include the most current version of ASTM D7380-15 Standard Test Method for Soil Compaction Determination at Shallow Depths Using 5-lb (2.3 kg) Dynamic Cone Penetrometer (ASTM International, 2015) and ASTM D6951/D6951M Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications (ASTM International, 2015).

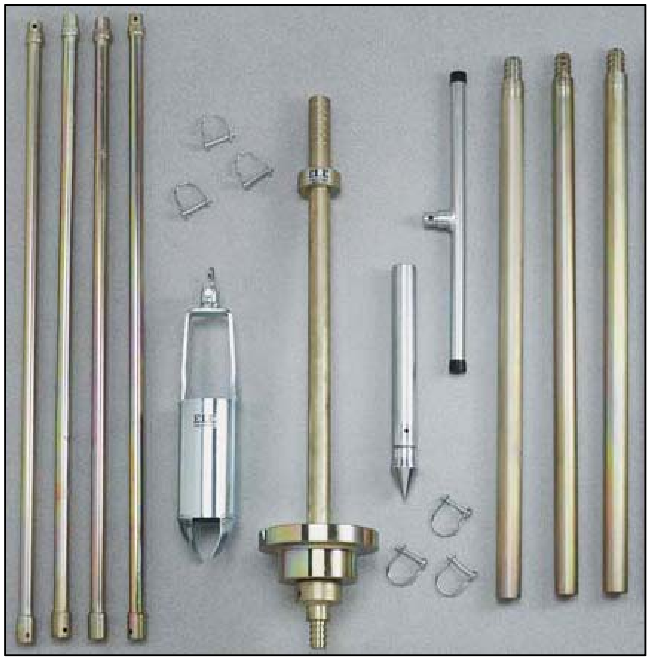


Figure 8.6: *Example of a dynamic soil cone penetrometer set with soil auger (Source: ELE International).*

The Cone Penetration Test using either a hand-held electronic static soil cone penetrometer or dynamic soil cone penetrometer is the recommended method for testing soil compaction in LID BMPs. For BMPs that cover extensive areas (e.g., enhanced swales, vegetated filter strips and soil amendments), assessing soil compaction by bulk density testing of core samples becomes impractical due to the large number of samples required and the considerable effort and cost involved in sampling, sample processing and laboratory testing. In bioretention and dry swales, which feature filter media (i.e., very sandy soil), collecting intact soil core samples is problematic, which makes measurement through bulk density testing of soil cores infeasible in most cases. While using a hand-held mechanical static cone penetrometer (i.e., hand penetrometer) provides a quick means of gauging soil strength (i.e., compaction) in the field (e.g., during construction), they are cited as being cumbersome to use (in terms of both effort and time) to assess extensive areas (USDA, 2005). The ease of use (single operator) and data management functionality provided by modern hand-held electronic static soil cone penetrometer sets make them preferable for testing large or multiple BMPs at one time over mechanical static and dynamic soil cone penetrometers.

Maximum soil cone penetrometer readings should be taken at each testing location at the soil surface (i.e., surface resistance) and through the full depth of soil present (i.e., sub-surface resistance), within a day or two after a heavy rainfall event. To evaluate soil compaction for bioretention, dry swales and enhanced swales, take measurements in at least five (5) locations or at a rate of one sample for every twenty-five (25) square metres (m^2) of vegetated BMP area, evenly distributed over the BMP surface. For vegetated filter strips, soil amendment areas, and grassed permeable pavements measurements should be made in at a rate of one for every 250 m^2 of vegetated BMP area, evenly distributed over the

BMP surface. Measurement locations should be recorded on the field data form, including a plan view sketch of the BMP showing the spatial distribution of measurements.

Maximum readings that exceed the values described in Table 8.3 indicate that the soil has been compacted to a degree that limits plant root growth. If any penetrometer maximum resistance reading exceeds the value corresponding to the relevant soil texture classification, as described in Table 8.3, steps should be taken to reverse compaction in that location. Compaction can be reversed through techniques such as tilling with a rototiller, scarifying with a subsoiler, chisel plow or backhoe, or excavation and replacement with uncompacted soil.

Table 8.3: *Acceptable soil cone penetrometer readings by soil texture class.*

Surface Resistance [1]	Sub-surface Resistance [1]		
All soil textures	Sandy *(includes loamy sand, sandy loam, sandy clay loam and sandy clay)*	Silty *(includes loam, silty loam, silty clay loam, and silty clay*	Clayey *(includes clay loam and clay)*
≤ 110 PSI	≤ 260 PSI	≤ 260 PSI	≤ 225 PSI
≤ 7.7 kg/cm²	≤ 18.3 kg/cm²	≤ 18.3 kg/cm²	≤ 15.8 kg/cm²
≤ 758 kPa	≤ 1793 kPa	≤ 1793 kPa	≤ 1551 kPa

Notes:

1. Adapted from Gugino et al. (2009).
2. PSI = pounds per square inch (lb/in²)
3. kg/cm² = kilogram per square centimetre
4. kPa = kilopascals

Bulk Density

A more expensive and time-consuming, but potentially more accurate test of soil compaction is to collect soil cores and send them intact to a soil testing laboratory for analysis of bulk density and PSD (i.e., % sand, % silt, % clay). Bulk density is the ratio of the dry mass of a soil sample to the total soil volume and is expressed in units of mass per unit volume (e.g., g/cm³). The bulk density of soil depends greatly on the mineral composition and degree of compaction. It is important to note that bulk density is not an intrinsic property of a soil as it can change depending on how the sample is handled. For example, if a soil core sample is disassociated through agitation during collection or transport, this changes the bulk density of the sample. Therefore, to accurately determine bulk density from soil sampling, soil cores must be delivered to the laboratory intact.

To determine if soil compaction is excessive using the laboratory test results for bulk density, the texture classification of the soil also needs to be known, which is determined through a PSD test (see Section 8.2.4). If soil texture is not known, a composite sample representative of the entire soil component of the BMP should be submitted for laboratory testing of PSD along with soil cores for bulk density testing.

Intact soil core samples should be collected through the full depth of soil present in at least five (5) locations, or at a rate of one reading for every twenty-five (25) square metres of vegetated BMP area, evenly distributed across the surface. Most soil corers can only sample approximately 30 cm of soil at a time so multiple core samples are needed at each testing location where soil depth exceeds 30 cm. As part of Assumption inspections, samples should be taken only after all grading operations have been completed and ideally before planting has occurred.

The acceptable laboratory method for determining soil bulk density is ASTM D7263-09 Standard Test Methods for Laboratory Determination of Density (Unit Weight) of Soil Specimens (ASTM International, 2009). An acceptable field method for in-situ soil bulk density testing is provided in ASTM D2937-10 Standard Test Method for Density of Soil in Place by the Drive-Cylinder Method (ASTM International, 2010). Although this method is the most simple to perform in the field, it is not suitable for use in organic, coarse or friable soils that are either prone to compaction during sampling or difficult to retain in soil core sample sleeves or cylinders. If the volume of extracted soil is not known, there are a number of other suitable methods, such as ASTM D2167-15 Standard Test Method for Density and Unit Weight of Soil in Place by the Rubber Balloon Method (ASTM International, 2015), and ASTM D6938-15 Standard Test method for in Place Density and Water Content of Soil and Soil Aggregate by Nuclear Methods (ASTM International, 2015).

Once bulk density test results are available, which typically requires between 2 to 4 weeks turnaround time when done by laboratory testing, it is possible to use the bulk density values to determine if the soil is overly compacted. This is done by comparing measured results to recommended maximum allowable values. Figure 8.7 describes the relationship between soil texture and Maximum Allowable Bulk Density. Maximum Allowable Bulk Densities in Figure 8.7 are based on 95% of the bulk density value at which growth limitations are expected for an average range of plant material (Daddow and Warrington, 1983). To calculate the maximum allowable bulk density for a soil:

1. Obtain a laboratory analysis of the grain size distribution (% sand, silt and clay);
2. Sketch a parallel line for each percentage along the appropriate axis on Figure 8.7, and;
3. At the point of intersection, interpolate a value between the isodensity lines.

If any bulk density test results exceed the Maximum Allowable Bulk Density value for the corresponding soil texture classification (see Figure 8.7), steps should be taken to reverse soil compaction in that location. Compaction can be reversed through techniques such as tilling with a rototiller, scarifying with a subsoiler, chisel plow or backhoe, or excavation and replacement with uncompacted soil.

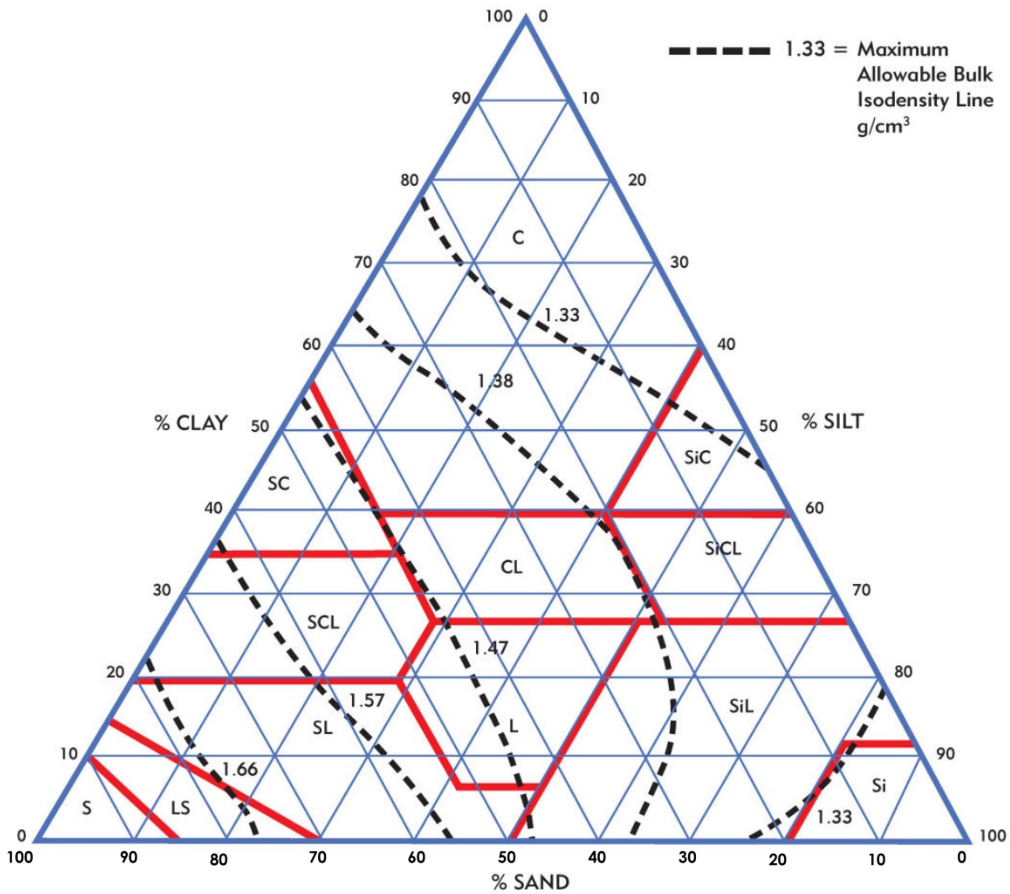


Figure 8.7: *Maximum allowable bulk density values by soil texture class (Source: The Sustainable Sites Initiative).*

8.2.4 Texture

Many of the physical and chemical properties of soil are affected by soil texture. The soil component of bioretention, dry swales and green roofs must meet very specific design specifications related to texture in order for the BMP to achieve drainage and water treatment performance targets. If the soil texture is too fine (i.e., contains more silt- and clay-sized particles than specified) it may have low permeability and drain too slowly or retain too much water for excessively long periods of time. If the soil texture is too coarse (i.e., contains more sand and gravel-sized particles than specified) it will have high permeability and may drain too quickly to provide adequate treatment of run-off, and may not retain enough water between storm events to sustain healthy vegetation cover. A critical part of Construction, Assumption and Verification inspections involves sampling and testing the soil component of BMPs to ensure it meets design specifications related to texture or is still within acceptable ranges for important gradations (e.g., percent silt- and clay-sized particles).

Soil texture is most accurately characterized by submitting a representative sample to a soil laboratory for a particle-size distribution (PSD) test. Other commonly used terms for the PSD test by soil laboratories are "Particle-Size Analysis", "Grain-Size Distribution" and "% Sand, % Silt, % Clay". For bioretention filter media and green roof growing media, "Sand Fraction Analysis" should also be requested. Acceptable methods for determining PSD of a soil sample are provided in ASTM D6913-04(2009)e1 Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis (ASTM International, 2009) and ASTM D7928-16, Standard Test Methods for Particle Size Distribution (Gradation) of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis (ASTM International, 2016). These methods are recommended for use in inspection and testing of LID BMPs because they include assessment of the pebble-sized particles of the soil (i.e., particles that are greater than 2 mm in diameter). Training on these procedures is available in ASTM D422-63(2007)e2 Standard Test Method for Particle-Size Analysis (ASTM International, 2007).

Most soil laboratories will summarize PSD test results according to the proportions of the sample made up of pebble/gravel-, sand-, silt- and clay-sized particles. When Sand Fraction Analysis is requested, a more detailed breakdown of gradations of sand-sized particles is provided, which is important for evaluating the acceptability of filter media for bioretention and dry swales. Figure 8.8 describes the Wentworth soil particle-size classification system (Wentworth, 1922) that should be used to classify pebble, sand, silt and clay fractions of a soil sample.

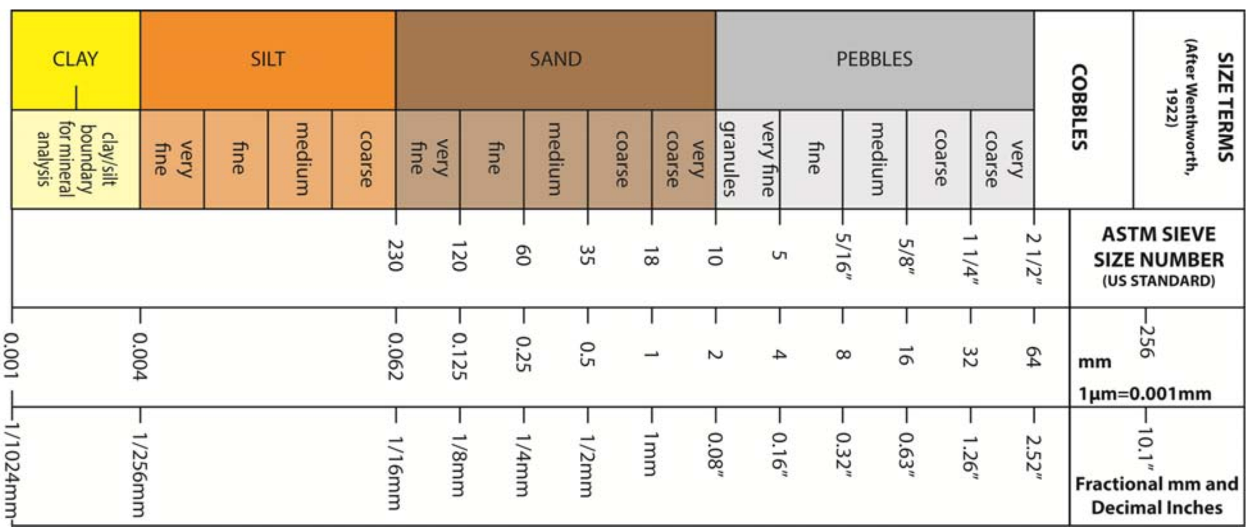


Figure 8.8: *Soil particle-size classification system (Adapted from Wentworth, 1922).*

As part of Construction inspections, if laboratory testing indicates any soil texture-related parameter is not within the design or product specification ranges, notify the media or topsoil supplier, issue a "do not install" order to the construction site supervisor and contact the design professionals and property owner or project manager to determine corrective actions.

As part of Assumption and Verification inspections, if laboratory testing indicates any soil texture-related parameter is not within the design or product specification ranges, or the Acceptance Criteria ranges (Table 8.1), schedule FIT work to do further sampling and testing to determine the affected area and depth and decide on corrective actions. Corrective actions for bioretention and dry swale filter media where the proportion of silt- and clay-sized particles is too high may involve removal of mulch, stone cover and plantings and tilling the top 20 to 30 cm, or removal and replacement of part or all of the filter media with material that is within acceptable tolerance ranges of design specifications.

8.2.5 Organic Matter

Organic matter is matter that has come from a once-living organism (i.e., plants and animals), is capable of decay or the product of decay, or is composed of organic compounds. Once it has decayed to the point at which it is no longer recognizable it is called soil organic matter. When the organic matter has broken down into a stable substance that resists further decomposition it is called humus. Soil organic matter comprises all of the organic matter in the soil, exclusive of the material that has not yet decayed (i.e., surface litter). It can be divided into three general pools (Figure 8.9): living biomass of micro-organisms, fresh and partially decomposed residues (the active fraction), and the well-decomposed and highly stable humus (USDA, 2015).

The structure, drainage and fertility characteristics of soil are all highly affected by organic matter content. In LID BMPs, if the soil does not contain enough organic matter it will lack porosity, water holding capacity and be difficult to maintain healthy vegetation cover without addition of chemical fertilizers. When organic matter content is too high, the soil may leach nutrients into the water that infiltrates through it, potentially contributing to nutrient loads to receiving waters rather than reducing them. So an important part of Construction, Assumption and Verification inspections involves sampling and testing the soil component of BMPs to ensure it meets the design specification for organic matter, or determine if it is still within an acceptable range.

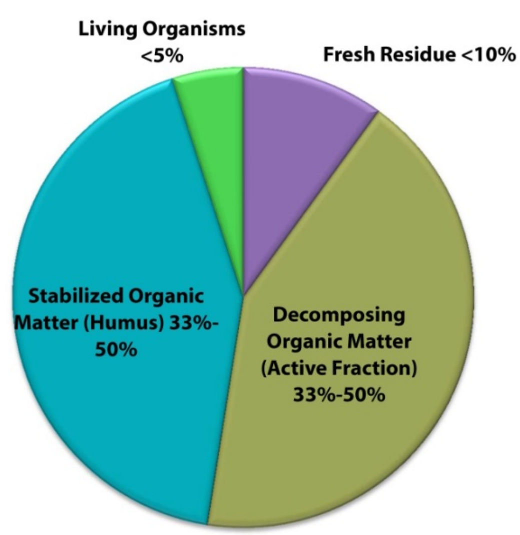


Figure 8.9: *Components of soil organic matter (Adapted from: USDA).*

To determine if the soil component of an LID BMP meets design specifications or is within an acceptable range for organic matter, representative samples must be collected and submitted to an accredited Ontario soil testing laboratory for soil organic matter analysis (see Appendix A for list). The recommended test method depends on the organic matter content of the soil sample. When organic matter is <7.5% by dry weight, the Walkley-Black method (Walkley, 1947) using a routine colorimetric determination procedure is acceptable. When organic matter is ≥7.5% testing must be done by a loss on ignition (LOI) method (OMAFRA, 2006). Testing soil organic matter by LOI method involves drying a sample, typically at 105 to 120 ◦C for 2 hours, measuring the dry weight, igniting and ashing the dry sample, typically at between 360 to 425 ◦C for 10 to 16 hours (OMAFRA, 2006; McLachlin, 2016; Wright, 2016) in a muffle furnace (Figure 8.10) and then reweighing the sample to determine the change in weight. The weight loss value (i.e., LOI value) is then used to calculate the organic matter content value based on the relationship between LOI and soil organic carbon established for the region through extensive testing of soil samples by the Walkley-Black method (McLachlin, 2016; Wright, 2016), with results reported as percent organic matter (%OM) by dry sample weight. Acceptable procedures for testing organic matter content of soils by both the Walkley-Black method and LOI method are provided by North Central Regional Research Publication No. 221 (Combs and Nathan, 2012). Acceptable procedures for testing organic matter content of compost or highly organic soils is provided by ASTM D2974-14, Standard Test Methods for Moisture, Ash, and Organic Matter of Peat and Other Organic Soils (ASTM International, 2014) and United States Department of Agriculture (USDA, 2002).

Figure 8.10: *Crucibles filled with soil, prepared for a loss on ignition test (Source: Pitchcare.com).*

As part of Construction inspections, if laboratory testing indicates soil organic matter content is not within the design or product specification range, notify the media or topsoil supplier, issue a "do not install" order to the construction site supervisor and contact the design professionals and property owner or project manager to determine corrective actions.

As part of Assumption and Verification inspections, <u>if laboratory testing indicates soil organic matter content is not within the design or product specification range, or the Acceptance Criteria range (Table 8.1), schedule FIT work to do further sampling and testing to determine the affected area and depth and decide on corrective actions</u>. Corrective action where organic matter is lower than the design/product specification or Acceptance Criteria involves amending the soil with compost. Detailed guidance on implementing compost soil amendments can be found in *Preserving and Restoring Healthy Soil: Best Practices for Urban Construction* (TRCA 2012). Amendments to green roof growing media to address organic matter content deficiency should be prescribed by the designer, product vendor or media supplier. Where organic matter is higher than the design/product specification or Acceptance Criteria, natural or simulated storm event testing should be undertaken (Section 8.5) that includes sampling and testing of nutrient concentrations (i.e., Phosphorus, Nitrogen, Soluble Salts) in sub-drain or surface flows from the BMP to evaluate if the exceedance is negatively impacting effluent quality.

8.2.6 Soil pH

Soil pH is a measure of the hydrogen ion concentration of a mixture of soil and water. A neutral soil has a pH value of 7.0. An acidic soil has a pH less than 7 and a basic soil has a pH greater than 7.

Soil pH is an important parameter that affects soil fertility. It influences the availability of nutrients needed to sustain plants and soil micro-organisms. It also affects the solubility of some elements which, in extreme scenarios, can reach levels toxic to plants and soil micro-organisms and increases the mobility and the potential for leaching of pollutants such as metals into the groundwater system. In humid temperate regions, the optimum soil pH range for most plants is between 6.0 and 7.5 (Craul, 1999). More acidic soils inhibit the solubility of potassium, sulfur, calcium, magnesium and molybdenum, while increasing the solubility of iron, manganese, boron, copper and zinc (Figure 8.11). Additionally, the solubility of phosphorus and nitrogen are reduced in both acidic and basic (i.e., alkaline) soils.

Design specifications for the soil component of LID BMPs pertaining to pH are intended to ensure its fertility and suitability for maintaining healthy vegetation cover. Where soil pH deviates from design specification, vegetation cover may be spotty or uneven, growth may be stunted, or in extreme cases, plantings may not survive and vegetation cover becomes dominated by weeds. To ensure the soil will support the growth of plantings, which contributes to the drainage and water treatment performance of the BMP and adds aesthetic value, testing of soil pH should be done as part of Construction, Assumption and Verification inspections.

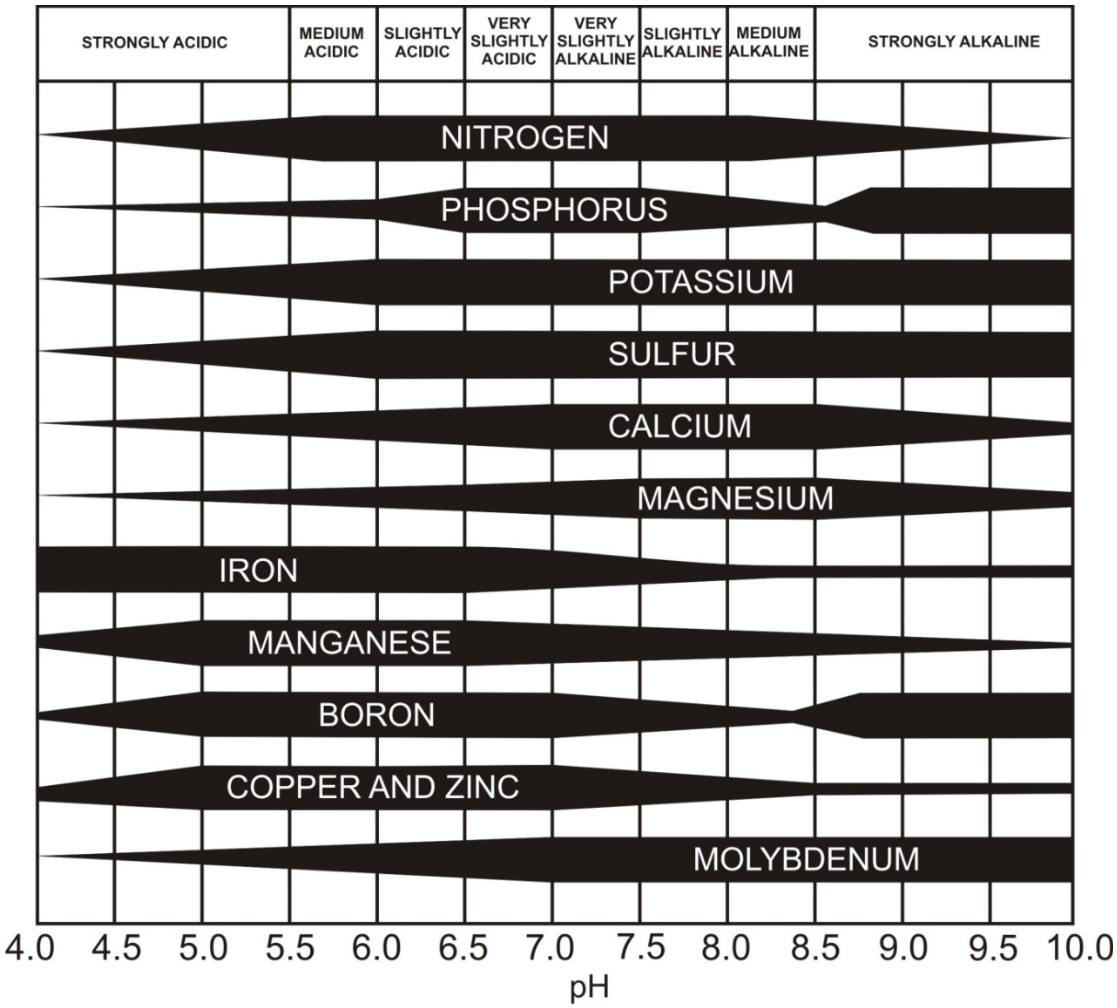


Figure 8.11: *Effects of soil pH on nutrient availability.*

Soil pH can be determined in the field using inexpensive soil pH testing kits (Figure 8.12) where a small sample of surface soil is mixed with water and reagents which change colour according to the acidity/alkalinity. The soil pH value is determined by comparing the colour and shade to calibrated scales. Soil pH can also be determined using a portable pH meter (Figure 8.12) which involves inserting a rod into a soil-water slurry mixture. Such soil pH tests should be conducted by creating a shallow (5 to 10 centimetre deep) hole in the soil, filling it up with distilled water, stirring to create a slurry mixture, inserting the pH meter rod into the slurry mixture and recording the value displayed on the meter. Alternatively, surface samples can be submitted to a soil testing laboratory accredited by the province of Ontario for testing by saturated paste method (OMAFRA, 2006). An acceptable procedure for testing soil pH is provided in ASTM D4972 - 13 Standard Test Method for pH of Soils (ASTM International, 2013).

Figure 8.12: *Examples of soil pH testing equipment. Left: Soil pH test kit (Source: Rapitest); Right: Soil pH meter (Source: Houston Gardening).*

For soils found through testing to not be within the design or product specification range or Acceptance Criteria range (Table 8.1), corrective actions are only needed if problems with vegetation cover, condition or composition (i.e., dominance by weeds) are also detected through visual inspection. Where vegetation cover is poor, unhealthy or dominated by weeds and soil pH is lower than the design/product specification or Acceptance Criteria ranges, corrective action involves amending the soil with ground limestone to raise the pH back to neutrality. Where soil pH is higher than the design/product specification or Acceptance Criteria ranges, corrective action involves amending the soil with sulphur or compost to lower the pH back to neutrality. Amendments to green roof growing media to address problems with soil pH and vegetation should be prescribed by the designer, product vendor or media supplier.

8.2.7 Cationic Exchange Capacity

Cationic exchange capacity (CEC) is an indicator of the capability of the soil to retain dissolved, positively charged elements such as metals, which are a common pollutant in stormwater runoff. Soil has the ability to retain dissolved metals due to the negative charge of clay and organic particles. Positively charged dissolved metals ions (i.e., cations) are attracted to the negatively charged soil particles which can cause them to be removed from solution and retained in the soil. CEC is influenced by soil texture (higher in fine textured soil), organic matter content (higher in organic soil), and pH (lower in acidic soil). Soils with high CEC are able to retain a larger proportion of dissolved metals and other positively charged pollutants, while soils with low CEC will retain less. The cationic exchange capacity of a soil sample is the sum of the exchangeable cations in the sample and expressed in milliequivalents of positive charge per 100 grams of soil.

Design specifications for the soil component of LID BMPs pertaining to CEC are intended to ensure the soil has adequate capacity to remove positively charged dissolved pollutants from the stormwater they receive. Where soil CEC is too low, dissolved metals and other positively charged pollutants may not be well retained and the BMP will not provide the targeted water treatment performance. Causes of low CEC in the soil component of LID BMPs can include excessively coarse texture, deficient organic matter content or that the soil has become saturated with positively charged ions (i.e., dissolved metal retention capacity has been exhausted). To ensure LID BMPs will provide the targeted water treatment performance, soil sampling and submission for laboratory testing of CEC by a soil testing laboratory accredited in the province of Ontario should be done as part of Construction, Assumption and Verification inspections.

A commonly used laboratory test method is to saturate a sample of the soil with a known quantity of cations and measure the amount retained by the soil. An acceptable test method is provided in ASTM D7503-10 Standard Test Method for Measuring the Exchange Complex and Cation Exchange Capacity of Inorganic Fine-Grained Soils (ASTM International, 2010). Descriptions of acceptable laboratory equipment for measuring CEC are described in the Soil Fertility Handbook (OMAFRA, 2006).

As part of Construction inspections, <u>if laboratory testing indicates soil CEC is not within the design or product specification range, notify the media or topsoil supplier, issue a "do not install" order to the construction site supervisor and contact the design professionals and property owner or project manager to determine corrective actions.</u>

As part of Assumption and Verification inspections, <u>if laboratory testing indicates soil CEC is not within the design or product specification range, or Acceptance Criteria range (Table 8.1), schedule FIT work to do further sampling and testing to determine the affected area and depth and decide on corrective actions</u>. Corrective action could involve amendment of the soil with compost or removal and replacement of an uppermost portion of the soil with material that is within the design or product specification range. Corrective actions to address CEC deficiency in green roof growing media should be prescribed by the designer, product vendor or media supplier.

8.2.8 Extractable Phosphorus

Phosphorus (P) is an essential soil nutrient that is necessary for sustaining plants and soil organisms. Sources of phosphorus in soil include minerals, organic matter, decomposing plant residues, manure and chemical fertilizers.

Too little phosphorus in soil reduces photosynthesis and respiration rates of plants, resulting in delayed maturity and reduced quality of foliage. Phosphorus is especially important in the early developmental stages of plants by stimulating seed germination, root formation, seedling growth, flowering, fruiting and seed development (Busman et al., 2009). Phosphorus utilized by plants becomes part of the foliage and roots. As foliage and roots decompose and becomes soil organic matter some of the P is converted to soluble, inorganic forms through mineralization. Phosphorus availability (i.e., solubility) is reduced at both high and low pH levels (Figure 8.11), so neutral soils are ideal for sustaining plants.

In natural systems like soil and water, phosphorus exists primarily as phosphate that is attached to soil particles or in the organic (i.e., solid) form as decaying organic matter and is not very soluble in water

(Busman et al., 2009). However, soil water and surface water usually contain low concentrations of inorganic, soluble (i.e., dissolved) phosphorus.

Although P is essential for plant growth and soil health, mismanagement can pose a threat to water quality in sensitive receiving waterbodies (i.e., lakes and rivers). When soil P is over abundant, it can be leached by infiltrating water and transported to surface waterbodies in its dissolved form by interflow or in its solid form (e.g., associated with soil particles) by surface runoff and erosion, thereby contributing to nutrient loading. When P concentration in a receiving waterbody becomes elevated, excessive growth of algae and aquatic plants often results. High levels of algae reduces water clarity and can lead to decreases in dissolved oxygen (i.e., eutrophication), conditions that can be very detrimental to fish populations and other beneficial uses of water resources.

Phosphorus is retained in soils by adsorption (i.e., attachment to soil particles) and chemical precipitation (Erickson et al. 2013). The presence of clay particles and organic matter increases the capacity of the soil to retain phosphorus, which reduces leaching and transport to receiving waters through interflow.

To help ensure LID BMPs sustain healthy vegetation cover while not contributing substantially to nutrient loading of receiving waters, the quantity of extractable (i.e., available) P in the soil component needs to be measured and compared to design specifications or acceptance criteria (Table 8.1).

For bioretention and dry swale, enhanced swale, vegetated filter strip and soil amendment BMPs, soil P should be measured as extractable phosphorus. Extractable phosphorus is a term referring to the portion that is easily available to organisms like plants and algae (i.e., available) that are present in a lake, river, stream or wetland and is the measure of immediate concern to water quality. The quantity of extractable P is determined through acid or base extraction of a sample and testing the concentration in solution by a soil testing laboratory. Commonly used extraction methods on soil samples are the Bray and Kurtz P-1 procedure for non-calcareous soil (Bray and Kurtz, 1945) or the Sodium Bicarbonate (Olsen) method for calcareous soil (Olsen *et al.,* 1954). The Sodium Bicarbonate (i.e., Olsen) method is recommended as the default to use for typical Ontario soils (OMAFRA, 2006). Calcareous soils are mostly or partly composed of calcium carbonate (i.e., lime or limestone). The Sodium Bicarbonate (Olsen) extraction method should be used if the soil contains more than 2% calcium carbonate (Frank et al., 2012). Modern and acceptable procedures for both types of extractions are provided by North Central Regional Research Publication No. 221 (Frank et al., 2012). Soil P results are typically reported in units of concentration as orthophosphate.

For green roof growing media, the Saturated Media Extract (SME) method should be used (Green Roofs for Healthy Cities, 2011). In this extraction procedure, a sample of the media is brought to saturation with deionized water containing a small amount of Pentetic acid (i.e., DTPA) to enhance extraction of micro-nutrients (Warnacke, 1995). The SME procedure should also be used to measure concentrations of soluble salts and nitrogen for green roof growing media (Green Roofs for Healthy Cities, 2011).

As part of Construction inspections, if laboratory testing indicates the extractable phosphorus concentration is not within the design or product specification range, notify the media or topsoil supplier, issue a "do not install" order to the construction site supervisor and contact the design professionals and property owner or project manager to determine corrective actions.

As part of Assumption and Verification inspections, for soils found through testing to be below the design or product specification range, or Acceptance Criteria range (Table 8.1), corrective actions are only needed if problems with vegetation cover, condition or composition (i.e., dominance by weeds) are also detected through visual inspection. Where vegetation cover is poor, unhealthy or dominated by weeds and soil P is lower than the design specification or Acceptance Criteria, schedule FIT work to do further sampling and testing to determine the affected area and depth and decide on corrective actions. Depending on the findings from FIT work, corrective action could involve amending the soil with compost or other fertilizer. Detailed guidance on implementing compost soil amendments can be found in *Preserving and Restoring Healthy Soil: Best Practices for Urban Construction* (TRCA 2012). Amendments to green roof growing media to address P deficiency should be prescribed by the media manufacturer or product vendor. Where soil P concentration is found to be higher than the Acceptance Criteria range (Table 8.1), and the BMP drains to a nutrient sensitive receiving water, continuous monitoring during natural or simulated storm events should be undertaken (Sections 8.5 & 8.6) that includes sampling and testing of nutrient concentrations (i.e., Phosphorus and Nitrogen) in sub-drain or surface flows from the BMP to evaluate if the exceedance is negatively impacting effluent quality and if corrective actions are warranted. Corrective action could involve incorporating a soil amendment that increases phosphorus retention, or replacement of part or all of the media or topsoil with material that is within the design or product specification.

8.2.9 Soluble Salts

All soils contain some water soluble salts which include essential nutrients for plant growth. When the concentration of water soluble salts exceeds a certain level, harmful effects on plant growth occur. A soil containing a high concentration of soluble salts is referred to as a saline soil. Salt-affected soils often result from the flow of salty water onto an area, either laterally (e.g., intentional infiltration of de-icing salt laden runoff in LID BMPs; de-icing salt laden runoff splashed onto roadside soils) or by artesian flow of salty groundwater onto topsoil.

The soluble salts design specification for the soil component of LID BMPs is intended to ensure its fertility and suitability for maintaining healthy vegetation cover. Where concentration of soluble salts deviates from design specification, vegetation cover may be spotty or uneven, growth may be stunted, or in extreme cases, plantings may not survive and vegetation cover becomes dominated by weeds. To ensure the soil will support the growth of plantings, which contributes to the drainage and water treatment performance of the BMP and adds aesthetic value, testing of soluble salts should be done as part of Construction, Assumption and Verification inspections.

Soluble salts concentration in soil can be assessed by measuring the ability of a soil and water mixture to conduct an electrical current, referred to as electrical conductivity (EC). The common unit for measurement of EC is milliSeimen per centimetre (mS/cm). The official international unit of measurement is Seimen per metre (S/m). One mS/cm is equal to one deciSiemen per metre (dS/m) or 0.1 Seimen per metre (S/m).

There are several methods available for preparing the soil and water mixture for EC testing. The method recommended for use in testing the soil component of LID BMPs for EC is using a 2:1 distilled water to soil ratio by volume slurry mixture based on OMAFRA recommendations for evaluating the fertility of cropland (OMAFRA, 2006). Other laboratory methods for measuring EC in engineered growing media (e.g., green roof growing media) include the Saturated Paste (SP) method (Whitley, 2012) or Saturated Media Extract (SME) method (Warnacke, 1995).

For green roof growing media, soluble salt concentration should also be measured using EC but with application of the SME method to prepare the soil and water mixture (Green Roofs for Healthy Cities, 2011). In this extraction procedure, a sample of the media is brought to saturation with deionized water containing a small amount of Pentetic acid (i.e., DTPA) to enhance extraction of micro-nutrients (Warnacke, 1995). The SME method should also be used to prepare soil water extraction solutions for measuring concentrations of extractable phosphorus and nitrogen for green roof growing media (Green Roofs for Healthy Cities, 2011).

As part of Construction inspections, if laboratory testing indicates soil soluble salts concentration is not within the design or product specification range, notify the media or topsoil supplier, issue a "do not install" order to the construction site supervisor and contact the design professionals and property owner or project manager to determine corrective actions.

As part of Assumption and Verification inspections, if laboratory testing indicates soil soluble salts concentration is higher than the design or product specification, or Acceptance Criteria (Table 8.1), corrective actions are only needed if problems with vegetation cover , condition or composition (i.e., dominance by weeds) are also detected through visual inspection. Where vegetation cover is poor, unhealthy or dominated by weeds and soluble salts are higher than the design or product specification or Acceptance Criteria, schedule FIT work to do further sampling and testing to determine the affected area and depth and decide on corrective actions. Depending on the findings from FIT work, corrective action could involve flushing the soil area with fresh water or removal and replacement of an uppermost portion of the soil with material that meets the design or product specification. Corrective actions to address soluble salts exceedance in green roof growing media should be prescribed by the designer, product vendor or media supplier.

8.2.10 Maximum Media Density

Maximum Media Density testing is only applicable to green roof growing media as part of a Construction inspection. Testing of this characteristic of growing media is important to green roof designers and approvers for load bearing capacity calculations for the roof structure the green roof will be installed on. If maximum media density is too high, the growing media may retain too much water or not drain quickly enough and could cause problems with the integrity of the roof structure.

To ensure the growing media is suitable for use on a given roof structure of set dead load bearing capacity, testing of maximum media density should be done as part of Construction inspections. Testing is typically done by the product manufacturer or vendor with results provided to approval authorities prior to delivery at the construction site. An acceptable method for assessing maximum media density is provided by ASTM E2399/E2399M-15 Standard Test Method for Maximum Media Density for Dead Load Analysis of Vegetated (Green) Roofing Systems (ASTM International, 2015). This method also includes acceptable procedures for assessing maximum water holding capacity, air-filled porosity and saturated media permeability. Table 8.1 provides Acceptance Criteria for maximum media density and all three of these related parameters.

As part of Construction inspections<u>, if laboratory testing indicates maximum media density does not meet the design specification, notify the supplier, issue a “do not install” order to the construction site supervisor and contact the approval authorities (e.g., municipality and/or property owner/manager) to determine corrective actions.</u> Corrective actions will depend on what factors are causing the exceedance, which can be diagnosed using the results for related parameters, maximum water holding capacity; air-filled porosity; and saturated media permeability. Corrective actions to address maximum media density exceedance in green roof growing media should be prescribed by the media manufacturer or product vendor.

8.3 Sediment Accumulation Testing

A primary function of LID BMPs is to capture and retain sediment, trash and debris that are suspended in stormwater runoff. Over time, sediment and natural debris accumulates in certain portions of a BMP, particularly in pretreatment devices (e.g., forebays, gravel diaphragms, hydrodynamic separators, filter strips, grass swales, catchbasin/manhole sumps) and at inlets, where inflowing runoff is slowed down and spread out, which promotes sedimentation of suspended materials by design. Without adequate inspection and maintenance (at least annually), accumulated sediment and debris in pretreatment devices and inlets can inhibit the flow of stormwater into the BMP or be transported onto the filter bed (Figure 8.13). Extensive sediment accumulation on the surface of a filter bed will eventually lead to drainage problems due to clogging of the filter media with fine-textured sediment. When sediment accumulation on the surface a filter strip or swale becomes excessive the BMPs begin to export sediment and associated pollutants to receiving waters rather than retain them.

Figure 8.13: *Example of excessive sediment accumulation at the inlet of a bioretention cell inhibiting flow of stormwater into the BMP.*

Therefore it is important to inspect LID BMPs for sediment accumulation as part of all types of inspections, which can be done visually (see Visual inspection Indicator sections C.3; C.4; C.13; C.29), but should also include periodic measurements of sediment depth in key components. As part of Construction inspections it helps to determine when pretreatment devices and construction site ESCs need sediment removal maintenance. As part of Assumption inspections it helps determine if the BMP is ready to be put into operation and assumed by the property owner/manager/municipality. As part of Routine Operation inspections it provides an indication of the volume of sediment removed and the means to estimate an accumulation rate, which can be used to optimize the frequency of routine maintenance work. As part of Verification inspections it provides an indication of whether or not the BMP is being adequately maintained and helps to diagnose the cause of any problems with drainage or vegetation detected through visual inspection or other types of testing.

8.3.1 Key Components, Test Methods and Equipment

Key components of LID BMPs that should be the subject of sediment accumulation testing (i.e., depth measurements) are described in Table 8.4 along with recommended test methods.

Depth measurements should be recorded on inspection field data forms provided in chapter 7 and used to determine if sediment removal maintenance is needed.

Specific to vaulted infiltration chamber systems, cisterns and pretreatment devices such as catchbasin or manhole sumps, measuring sediment depth by means that do not require entry into the structure are preferable from worker safety and level of effort perspectives. As described in Table 8.4, recommended methods for measuring sediment depth in such underground structures include using sludge samplers (e.g., a “sludge judge” sampler), probes from the surface or taking measurements from a pre-installed staff gauge (Figure 8.14) mounted on the structure wall and set to the bottom elevation. With knowledge of the dimensions of the structure, depth measurements can be used to estimate the volume of accumulated sediment and what portion of the retention capacity of the device this represents.

Measuring sediment depth in underground structures from surface access points is best done using the following "two prong" method (see Figure 8.15 for an illustration).

1. Vertically lower a rigid probe into the structure and press it through the sediment until the base elevation is reached
2. Mark the probe at a fixed reference point at the surface (e.g., rim of the access hatch, catchbasin or manhole).
3. Measure and record the length of probe inserted into the structure.
4. Attach a flat 20 to 30 cm diameter disc, like a secchi disk (Figure 8.16) to the probe or a length of rope and gently lower it into the structure, allowing it come to rest on the surface of the accumulated sediment.
5. Mark the probe or rope at the same fixed reference point used in step 2.
6. Measure and record the length of probe or rope inserted into the structure.
7. Subtract the value obtained in step 3 from the value obtained in step 6 to calculate the sediment depth.

It is important to note that Ontario Workplace Health and Safety regulations (O.Reg 632/05) require that any work involving entry into an underground structure (e.g., catchbasin, manhole, hydrodynamic separator, infiltration chamber system, cistern) can only be performed by staff trained in confined space entry and equipped with certified and recently tested safety equipment (i.e., harness, tripod, winch, multi-gas detector). Staff involved in sediment accumulation testing in underground structures must be adequately trained and equipped, even if "entry" only involves lowering equipment into the structure from the surface.

Table 8.4: *Key components and test methods for sediment accumulation testing by BMP type.*

LID BMP Type	Key Components	Recommended Test Method
Bioretention and dry swales; Enhanced swales; Vegetated filter strips	Inlets; Pretreatment devices	Use a tape measure or probe to measure the depth from the bottom elevation of the pretreatment device or surface of the filter bed (adjacent to the inlet structure), below any stone or mulch cover present, to the highest elevation of accumulated sediment present. For catchbasins, manholes and hydrodynamic separator pretreatment devices a sludge sampler (e.g., "sludge judge" sampler) should be used to sample the sediment and estimate depth accumulated in sumps. Record the measurement and remove the sediment if it exceeds trigger values for follow-up action.

	Filter bed	Use a tape measure or probe to measure sediment depth from the surface of the filter bed, below any stone or mulch cover present, to the elevation of accumulated sediment present in at least five (5) locations evenly distributed over the filter bed surface area. Record the measurements, calculate the mean sediment depth and compare to trigger values to determine if follow-up/corrective actions are needed.
Underground infiltration systems	Inlets; Pretreatment devices	Use tape measure or probe to measure the depth from the bottom elevation of the inlet pipe or pretreatment device, below any stone or mulch cover present, to the highest elevation of accumulated sediment present. For catchbasins, manholes and hydrodynamic separator pretreatment devices a sludge sampler (e.g., "sludge judge" sampler) should be used to sample the sediment and estimate depth accumulated in sumps. A measuring tape or staff gauge installed in the structure and set to the bottom elevation can provide another means of tracking sediment accumulation. Record the measurement and remove the sediment if it exceeds trigger values.
	Filter bed	(Applicable to vault-type infiltration chamber systems only) Use a tape measure or probe to measure sediment depth from the surface of the gravel bed to the elevation of accumulated sediment in at least five (5) locations evenly distributed over the bed surface area. Record the measurements, calculate the mean sediment depth and compare to trigger values to determine if follow-up/corrective actions are needed.
Cisterns	Cistern	From outside the cistern use a tape measure or probe to measure the depth from a fixed point (e.g., rim of the access hatch) to the bottom elevation of the cistern and to the highest elevation of accumulated sediment present. Subtract the two values to calculate the sediment depth. A sludge sampler (e.g., "sludge judge" sampler) may also be used to sample the sediment and estimate depth. A staff gauge installed on the cistern wall and set to the bottom elevation provides another means of measuring sediment depth that does not require entry into the confined space. Record the measurement and remove the sediment if it exceeds trigger values for follow-up action.

Figure 8.14: *Examples of staff gauges (Source: Hoskins Scientific Canada).*

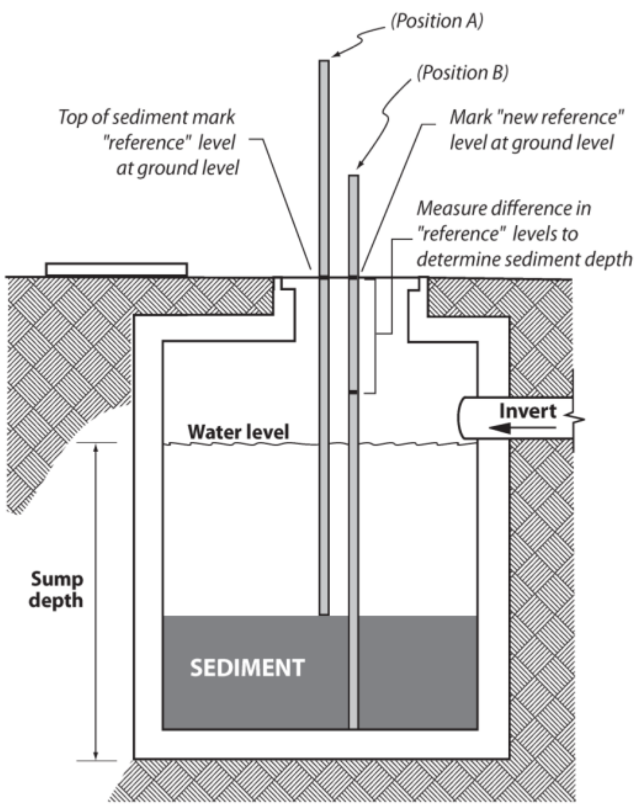


Figure 8.15: *Measuring sediment depth in a catchbasin by the two prong method (Source: King County, 2010).*

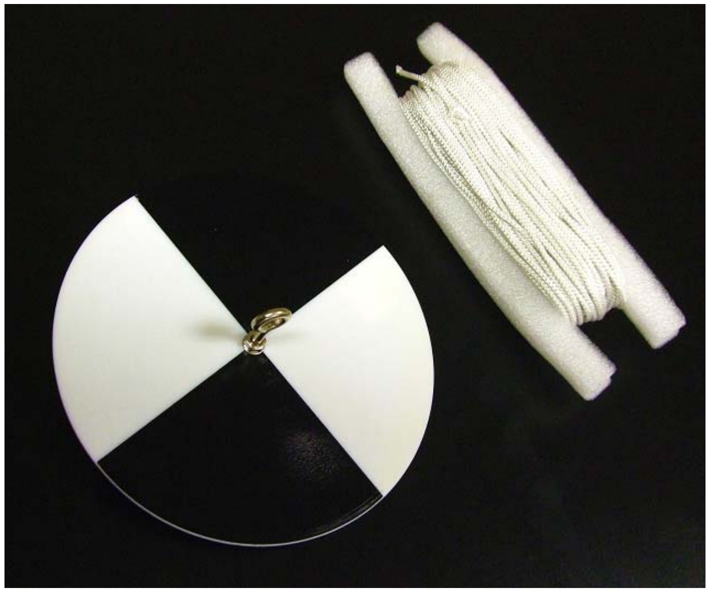


Figure 8.16: *Example of a secchi disk (Source: Wildco).*

Figure 8.17: *Example of a sludge sampler being used to inspect a hydrodynamic separator (Source: Minotaur Stormwater Services).*

Equipment needed for sediment accumulation testing can include the following:

- Safety apparel (hard hat, steel toed boots, gloves and eye protection)
- Safety cones or barriers (for restricting access around open hatches/grates/manhole covers)
- Clipboard, inspection field data forms, pens

- Pick shovel (for opening catchbasin grates or manhole covers)
- Measuring tape
- Probe (rigid)
- Secchi disk
- Sludge sampler (Figure 8.17)
- Rope
- Flashlight or headlamp
- Harness
- Tripod (certified and tested)
- Winch (certified and tested)
- Multi-gas detector (recently calibrated and tested)

<u>Sediment accumulation testing should be conducted frequently during construction (e.g., weekly and after any storm event of 15 mm depth or greater), as part of Assumption inspection work, once construction is fully completed and sediment accumulated on the CDA, in conveyances (e.g., gutters, catchbasins, storm sewers) and pretreatment devices has been removed, and as part of Routine Operation and Verification inspections.</u>

Sediment depth measurements collected at a BMP over the first few years of operation (e.g., at least 2 years) through Assumption and Routine Operation inspections provide the means of calculating a typical accumulation rate. This information provides an indication of the quantity of sediment retained over a given time period. It also provides an indication of whether or not the current frequency of routine sediment removal maintenance is adequate and the means of optimizing the frequency to provide adequate maintenance while minimizing effort and associated costs. To estimate the rate of sediment accumulation, at least two measurements are required. In most cases annual measurements taken over two or three years of routine operation (i.e., a fully stabilized and planted CDA) are all that is needed to estimate sediment accumulation rate.

8.3.2 Triggers for Follow-Up and Corrective Actions

The results of sediment accumulation testing can be used immediately to determine if sediment removal maintenance is needed or to determine other follow-up or corrective actions. Table 8.5 describes numerical triggers for follow-up and corrective actions and recommended tasks or actions, broken down by BMP component.

8.4 Surface Infiltration Rate Testing

For LID BMPs like bioretention and dry swales, enhanced swales, vegetated filter strips and permeable pavements, the rate at which stormwater infiltrates (i.e., percolates) through the BMP surface greatly affects its drainage performance. If the surface infiltration rate (i) is too low, inflowing stormwater will quickly begin to pond on the surface and, once the overflow outlet elevation is reached, will by-pass treatment by the BMP. In extreme cases the BMP may pond water on the surface for longer than 24 hours, creating nuisance conditions (e.g., poor vegetation cover, ice formation) and the potential for mosquito-breeding habitat. Causes of excessively low surface infiltration rates include use of soil during construction that does not meet design specifications, accumulation of fine sediment on the soil surface or in permeable pavement joints or pore spaces, and over-compaction of the soil, that can occur during construction or routine operation.

Therefore it is important to test the surface infiltration rate of LID BMPs as part of Assumption and Verification inspections. As part of Assumption inspections it helps determine if the BMP is ready to be assumed by the property owner. As part of Verification inspections it provides an indication of whether or not the surface drainage performance of the BMP is still within an acceptable range, if it is being adequately maintained, and to diagnose the cause of any problems with drainage or vegetation detected through visual inspection or other types of testing. Tests may also be done as part of FIT work to diagnose the cause of problems with drainage or vegetation, with the number and locations of test determined by the nature of the problem being investigated.

Table 8.5: *Sediment accumulation – triggers for follow-up and corrective actions.*

BMP Component	Trigger	Type of Structure	Follow-up and Corrective Actions [1]
Inlet	Sediment depth is ≥ 5 cm on the filter bed adjacent to the inlet (see Inlet Obstruction visual indicator protocol, section C.3)	Curb cut; Flush curb; Pavement edge; Pipe	Remove the accumulated sediment by shovel, vacuum or vacuum truck and estimate and record the quantity.
Pretreatment device	≥ 50% of retention capacity of the device is occupied by sediment and debris (see Pretreatment Sediment Accumulation visual indicator protocol, section C.4)	Forebay; Gravel diaphragm	Remove the accumulated sediment by shovel, vacuum or vacuum truck. Estimate and record the quantity.
		Vegetated filter strip; Grass swale	Remove the accumulated sediment by rake and shovel. Estimate and record the quantity.
		Catchbasin or manhole sump;	Schedule removal of accumulated sediment by vacuum or hydrovac truck.
		Hydrodynamic separator, in-line filter or isolator/ containment row	Schedule removal of accumulated sediment by hydrovac truck.
Filter bed	Mean sediment depth is ≥ 5 cm (see Filter Bed Sediment Accumulation visual indicator protocol, section C.13)	Filter media or swale surface	Remove the accumulated sediment by rake and shovel, vacuum , vacuum truck or small excavator. Estimate and record the quantity.
		Gravel bed surface (underground infiltration chambers)	Schedule removal of accumulated sediment by vacuum or hydrovac truck with JetVac pressure nozzle.
Cistern	Sediment depth is at the level of the distribution system intake when water level is at the lowest operating level (see visual indicator protocol section C.29)	Cistern	Schedule removal of accumulated sediment by vacuum or hydrovac truck with JetVac pressure nozzle.

Notes:

1. If standing water is present, the BMP component will need to be dewatered prior to or as part of the sediment removal procedure.

Surface infiltration rate testing involves estimating the saturated hydraulic conductivity (K_S) of the BMP surface through measurement at several locations and calculation of an average value. A single measurement can take anywhere from 15 minutes to several hours (Erickson et al., 2013) depending on soil or surface characteristics. Saturated hydraulic conductivity values can vary spatially by orders of magnitude depending on many factors, such as soil texture, plant root structure, compaction and soil moisture (Warrick and Nielsen, 1980; Asleson et al., 2009). So it is important to take several measurements for an individual BMP to represent the variation over the surface. Examination of individual measurements of K_S can also identify what portion of the BMP surface is draining too slowly or too quickly so that maintenance or rehabilitative efforts can be focused on only those areas to help minimize costs.

In bioretention practices with flat bottoms (e.g., cells, planters), a well installed at the surface of the filter media bed (Figure 8.18) can be used to measure surface ponding depth and duration using a pressure transducer water level logger. This provides the information needed to estimate filter bed surface infiltration rate, track it over time as the BMP ages and determine when rehabilitation is needed (when surface ponding drainage time exceeds 24 hours).

Time to drain water ponded on the surface of the filter media bed is derived from water level logger data. Conservative estimates of surface infiltration rate (i_S) of the filter media bed can be made by examining the time required to drain the last 50 mm (2") of surface ponded water and calculating the value (in mm/h) using Equation 8.2. Estimates are conservative because infiltration rates will be higher at greater ponding depths. To evaluate surface infiltration rate using a surface ponding well during a simulated storm event, the filter media bed should be thoroughly wetted prior to the test. Measurements of filter bed drainage rate and corresponding estimates of surface infiltration rate should be made following natural or simulated storm events that deliver enough water to the BMP to pond at least 75 mm of water on the surface of the filter media bed, in an effort to consistently approximate saturated soil flow conditions.

Equation 8.2: *Filter bed surface infiltration rate.*

Filter Bed Surface Infiltration Rate (i) = 50 mm / ΔT_{50}

Where;

ΔT_{50} = Time to drain last 50 mm of surface ponded water

$\Delta T_{50} = (T_2 - T_1)*24$

T_1 = Post-storm date and time (mm/dd/yyyy hh:mm:ss) when surface ponding water level reaches 50 mm in depth.

T_2 = Post-storm date and time (mm/dd/yyyy hh:mm:ss) when surface ponding is fully drained.

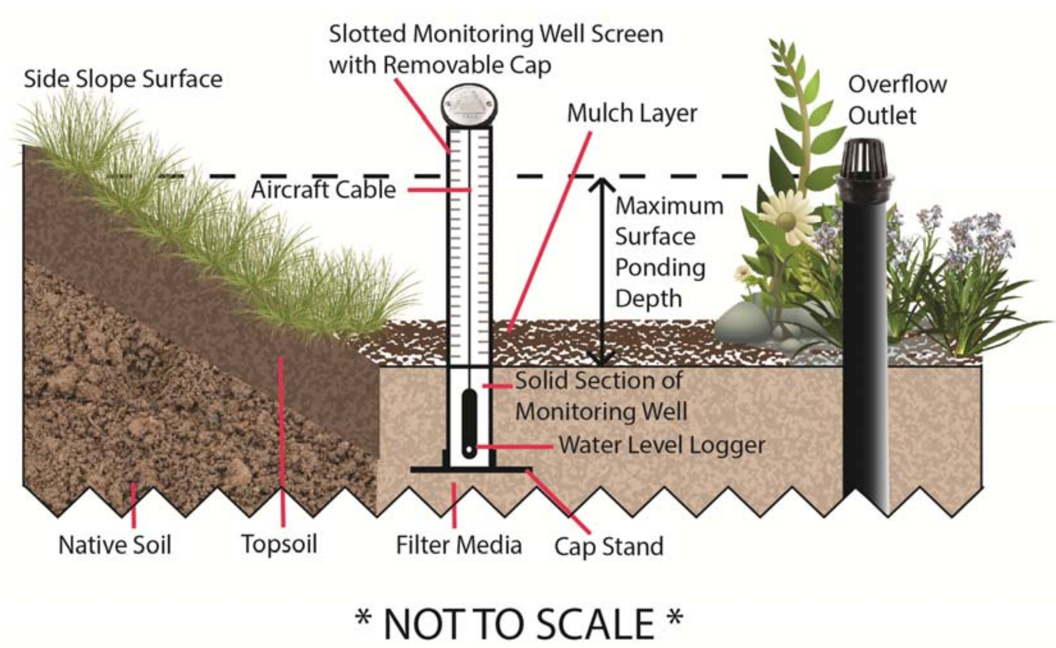


Figure 8.18: *Cross-section diagram of a surface ponding well installed in a bioretention cell.*

8.4.1 BMP Components and Test Methods

Key components of LID BMPs that should be the subject of surface infiltration rate testing are described in Table 8.6 along with recommended test methods.

Table 8.6: *Key components for surface infiltration rate testing by BMP type and test methods.*

LID BMP Type	Key Components	Recommended Test Methods
Bioretention and dry swales; Enhanced swales; Vegetated filter strips	Filter bed surface	Use an infiltrometer or permeameter to measure field saturated hydraulic conductivity (K_S) in at least 5 locations or at a rate of one measurement for every 25 m^2 of filter bed surface area, including inlet and lowest elevation areas. Compare mean and individual values to the design specification or trigger value (Table 8.9) to determine if follow-up tasks are needed.
Permeable pavements	Pavement surface	Use a single-ring infiltrometer to measure field saturated hydraulic conductivity (K_S) in at least 5 locations or at a rate of one measurement for every 250 m^2 of pavement surface area, evenly distributed. For permeable interlocking pavers, follow the procedure provided by ASTM C1781_C1781M – 15 (ASTM International, 2015). For pervious concrete or porous asphalt, follow the procedure provided by ASTM C1701_C1701M – 09 (ASTM International, 2009). Compare mean and individual values to the design specification or trigger value (Table 8.9) to determine if follow-up tasks are needed.

There are two major types of methods for testing surface infiltration rate; constant head and falling head methods (Table 8.7). A constant head test uses an instrument (permeameter or infiltrometer) to measure hydraulic conductivity until it approaches a steady state (i.e., field saturated conditions have be achieved). Double- and single-ring infiltrometers, Tension infiltrometer and the Guelph permeameter with tension disk are examples of constant head test methods for measuring saturated hydraulic conductivity (Ankeny, 1992). A falling head test uses an infiltrometer to measure the rate of water level decline over time. In-situ measurements of soil moisture should be taken before and after falling head tests to more accurately estimate saturated hydraulic conductivity values (Klute, 1986). The Modified Philip-Dunne infiltrometer (Ahmed et al., 2011) or single-ring infiltrometer are examples of falling head test methods.

An advantage of constant head test methods is that one does not need to measure soil moisture. Disadvantages are that they take longer to perform and require larger volumes of water than falling head tests. For comparison of various methods, refer to ASTM D5126/D5126M-90(2010)e1 Standard Guide for Comparison of Field Methods for Determining Hydraulic Conductivity in Vadose Zone (ASTM International, 2010). Details on standard test methods can also be found in Amoozegar and Warrick (1986).

Testing with an infiltrometer or permeameter produces a measurement of saturated hydraulic conductivity (K_S), which is typically reported in units of centimetres per second (cm/s). Infiltration rate (i) is typically reported in units of millimetres per hour (mm/h). <u>It is critically important to note that saturated hydraulic conductivity (K_S) and infiltration rate (i) are two different concepts and that conversion from one parameter to another cannot be done through unit conversion.</u> If the design specification is only available as an infiltration rate (e.g., ≥ 15 mm/h), the mean measured value for saturated hydraulic conductivity can be converted into an estimate of infiltration rate using the relationship described in Table 8.8 and Figure 8.20.

Field measurements of saturated hydraulic conductivity (K_S) are subject to considerable variation due to a variety of complicating factors (e.g., spatial variability, compaction, moisture content), so multiple measurements should be taken and used to calculate an average (mean) value. <u>For bioretention and dry swales, at least five (5) measurements should be taken, plus one for every 25 m^2 of filter bed surface area. For permeable pavements, at least five (5) measurements should be taken, plus one for every 250 m^2 of permeable pavement area</u>. Ideally, measurements should be taken soon after a storm event that thoroughly wets the full depth of soil.

Equipment needed for surface infiltration rate testing will vary depending on the chosen test method but can include the following:

- Safety apparel (steel toed boots)
- Safety cones or barriers (for restricting access when testing permeable pavements)
- Clipboard, inspection field data forms, pens
- Testing instrument (e.g., infiltrometer or permeameter) and instruction manual

- Stopwatch
- Water reservoir (e.g., truck mounted tank or cistern filled with water)
- Buckets or jugs (for filling the instrument)
- Plastic graduated cylinder (for measuring volume of water added during constant head infiltrometer tests)
- Soil moisture probe
- Fine sand (for even contact between Tension infiltrometer and soil surface)

Table 8.7: *Description of common methods for surface infiltration rate testing.*

Method	Description
Double Ring Infiltrometer (constant head)	The double-ring infiltrometer is made of two concentric tubes (Figure 8.19), typically of thin metal or hard plastic, that are both continuously filled with water such that a constant water level is maintained as water infiltrates into the soil (ASTM International, 2005). The rate at which water is added to the centre tube is measured to determine the infiltration rate. For detailed guidance on how to perform the testing, refer to ASTM D3385-09 Standard Test Method for Infiltration Rate of Soils in Field Using Double-Ring Infiltrometer (ASTM International, 2009) and ASTM D5093-15 Standard Test Method for Infiltration Rate of Soils in Field Using Double-Ring Infiltrometer with Sealed-Inner Ring. Accuracy is only moderate relative to permeameter methods (ASTM International, 2010) and results tend to be biased towards higher values due to lateral flow. Potentially requires large volume of water and significant length of time for each measurement to reach steady state.
Single Ring Infiltrometer (constant or falling head)	Similar to the double-ring infiltrometer, except with only one ring. Can be used to measure the vertical movement of water through a soil or permeable pavement. The standard design is a ring that is 30 cm in diameter and 20 cm tall, driven 5 cm into the soil or sealed to the surface of a permeable pavement and filled with water (Klute, 1986). For detailed guidance on how to perform the testing on permeable interlocking pavers, follow the procedure provided by ASTM C1781_C1781M – 15 (ASTM International, 2015). For pervious concrete or porous asphalt, follow the procedure provided by ASTM C1701_C1701M – 09 (ASTM International, 2009). Accuracy for soil testing is only moderate relative to permeameter methods (ASTM International, 2010) and results tend to be biased towards higher values due to lateral flow. Potentially requires large volume of water and significant length of time for each measurement to reach steady state when used for soil testing.
Modified Philip-Dunne Infiltrometer (falling head)	The Modified Philip-Dunne infiltrometer is falling head test device made of an open ended 50 cm long clear plastic cylinder with 2 mm thick walls, a 10 cm inner diameter and graduations, inserted into a machined metal base (Figure 8.19). Unlike the Philip-Dunne permeameter, which requires digging a borehole (i.e., not a surface infiltration test method), it is inserted 5 cm into the surface of the soil without the need for removing vegetation cover. Water level measurements in the tube can be obtained using the graduations on the side of the cylinder and a stopwatch, or continuously recorded through use of a data logger and pressure transducer installed in a piezometer tube.

	Measurements of soil moisture (e.g., using a handheld soil moisture probe) are needed before and after each test. Using relationships established by Ahmed and Gulliver (2011), the observed infiltration rate and initial and final soil moisture measurements are used to calculate a value for saturated hydraulic conductivity. A quicker test to perform than constant head tests. Superior to the single-ring infiltrometer falling head test as lateral flow is incorporated into the calculations.
Tension Infiltrometer (constant or falling head)	This test involves a porous disc of 10 or 20 cm diameter that is connected to a Marriotte bottle (water reservoir) and a bubbling tower where a negative pressure or tension is set (Figure 8.19). The porous disc must be placed in contact with the soil surface which usually requires removal of any vegetation and debris. In many cases it is necessary to place a thin layer of fine sand onto the soil surface to provide good contact between the disc and the soil. Infiltration rates are measured based on the water level drop in the water reservoir. The steady state infiltration rate into the soil is measured for two applied water pressures. To estimate saturated hydraulic conductivity the pressures need to be slightly negative (i.e., tensions) and it is recommended that successive pressures of -5 cm and -1 cm be used (Erickson et al., 2013). The measured steady state infiltration rates are used in equations derived by Reynolds and Elrick (1991) to calculate a value for saturated hydraulic conductivity. For detailed guidance on how to perform the testing, refer to Reynolds and Elrick (1991). The Mini-disc Tension infiltrometer (4.5 cm porous disc) uses a falling head method developed by Zhang (1997) to estimate saturated hydraulic conductivity. It is a quicker test to perform than the constant head method but potentially more difficult to achieve adequate contact with the soil surface.
Guelph Permeameter with Tension Disk (constant head)	The Guelph permeameter is another test device for measuring saturated hydraulic conductivity of a soil surface when used with a tension disc attachment (Figure 8.19). The method is similar to a Tension infiltrometer, but with water being directed to the tension disc from an inner or outer Mariotte reservoir, giving it the capacity to test low and high permeability soils (Soil Moisture Equipment Corp. 1986). Infiltration rates are calculated from monitoring the water level drop in the reservoir until a steady state is approached. Like the Tension infiltrometer method, tests are run with two applied tensions. Steady state infiltration rates from the two applied tensions are used to calculate a value for saturated hydraulic conductivity. Potentially requires large volume of water and significant length of time for each measurement to reach steady state.

Figure 8.19: *Examples of devices commonly used to test surface infiltration rate. Top left: Double-ring infiltrometer; Top right: Modified Philip-Dunne infiltrometer (Source: St. Anthony Falls Laboratory); Bottom left: Tension infiltrometer with data logger (Source: ICT International); Bottom right: Guelph permeameter tension disk attachment (Source: Hoskins Scientific).*

Table 8.8: *Approximate relationships between saturated hydraulic conductivity, percolation time and infiltration rate (*Source: OMMAH, 1997).

Saturated Hydraulic Conductivity, K_S (centimetres/second)	Percolation Time, T (minutes/centimetre)	Infiltration Rate, 1/T (millimetres/hour)
0.1	2	300
0.01	4	150
0.001	8	75
0.0001	12	50
0.00001	20	30
0.000001	50	12

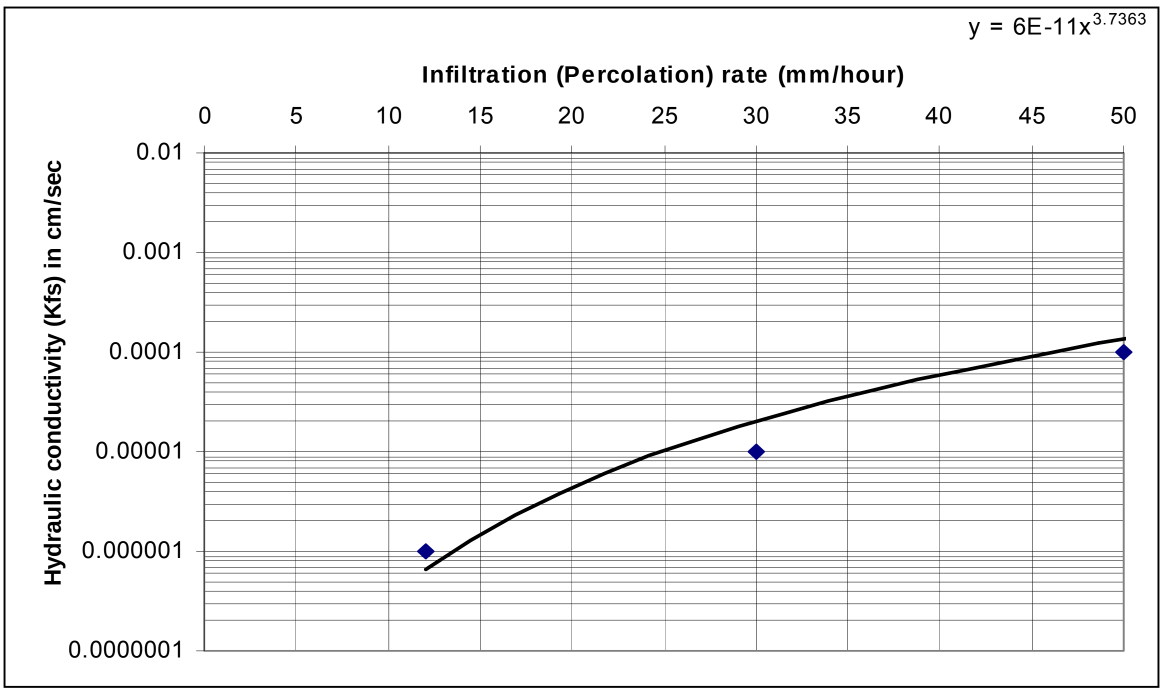


Figure 8.20: *Approximate relationship between infiltration rate and saturated hydraulic conductivity (Source: OMMAH, 1997).*

8.4.2 Triggers for Follow-Up and Corrective Actions

As part of Assumption inspections, the results of surface infiltration rate testing provide the means of confirming that the materials used to construct an LID BMP meet design specifications for permeability. As part of Verification inspections test results help to determine if the surface drainage performance of the BMP is still within an acceptable range. When combined with results from soil characterization and sediment accumulation testing and visual inspections, surface infiltration test results also help to determine when maintenance to address sediment accumulation on the surface of the BMP is needed. Accumulation of fine sediment at the BMP surface can cause a crust to form that greatly reduces the rate at which inflowing stormwater can infiltrate. Table 8.9 describes numerical triggers for follow-up by BMP type, and recommended corrective actions.

Table 8.9: *Surface infiltration rate – triggers for follow-up and corrective actions by BMP type.*

BMP Type	Trigger	Follow-up and Corrective Actions
Bioretention and Dry swales (filter media bed surface)	$i < 25$ mm/h; $K_S < 1 \times 10^{-5}$ cm/s $i > 203$ mm/h; $K_S > 0.02$ cm/s	When part of an Assumption inspection, issue a stop work order and contact the construction site supervisor, design professionals and property owner or project manager to determine follow-up tasks. Follow-up tasks involve scheduling FIT work to do further testing to determine the affected area and depth and decide on corrective actions. Corrective actions may involve removal of any accumulated sediment, mulch or stone cover and plantings and tilling of the top 20 to 30 cm of filter media to eliminate surface crusting or macropores and reduce compaction. Alternatively, removal and replacement of all or the uppermost 15 cm of filter media with material that meets design specifications may be necessary.
Enhanced Swales; Vegetated Filter Strips & Soil Amendment Areas (topsoil surface)	$i < 15$ mm/h; $K_S < 1.5 \times 10^{-6}$ cm/s	When part of an Assumption inspection, issue a stop work order and contact the construction site supervisor, design professionals and property owner or project manager to determine follow-up tasks. Follow-up tasks involve scheduling FIT work to do further testing to determine the affected area and depth and decide on corrective actions. Corrective actions may involve removal of any accumulated sediment and plantings and tilling of the topsoil to between 20 and 30 cm depth to eliminate surface crusting, increase porosity and reduce compaction. If testing indicates low organic matter content, topsoil should be amended with compost prior to tilling.
Permeable pavements (pavement surface)	$i < 250$ mm/h	When part of an Assumption inspection, issue a stop work order and contact the construction site supervisor, design professionals and property owner or project manager to determine follow-up tasks. Follow-up tasks involve scheduling FIT work to do further testing to determine the affected area and decide on corrective actions. Corrective action should first involve thoroughly sweeping and vacuuming the affected pavement area when dry in an attempt to remove sediment accumulated in the pavement joints or pore spaces. If vacuuming does not restore surface infiltration rate to an acceptable value (i.e., ≥ 250 mm/h) try manual or pressure washing means to remove surface crust and sediment from paver joints or pore spaces. In extreme cases, removal of the affected portion of the surface course and bedding and reinstallation with materials that meet design specifications may be necessary.

8.5 Natural or Simulated Storm Event Testing

For LID BMPs that receive stormwater via conveyances like gutters, concrete inlets and leader pipes from roofs or catchbasins (i.e., bioretention and dry swales, enhanced swales, underground infiltration systems) it is critically important to confirm that these conveyances have been designed and constructed properly. If the conveyances are obstructed or improperly graded or constructed, the BMP may not receive flows from their CDA or a significant quantity of stormwater may by-pass treatment. This is particularly important for underground BMPs where inlets are not visible from the surface. Therefore, confirming that these types of BMPs actually receive stormwater from their CDA should be a part of Assumption and Verification inspections.

The simplest approach to confirming that conveyances to LID BMPs are constructed properly and functioning well is through observation of the path of water flow and measuring water level in the BMP during a natural storm event. If timelines for completing inspections cannot be coordinated to coincide with a natural storm event, an alternative approach is to simulate a storm event over the CDA by directing water onto it through the use of a water tanker truck (Figure 8.21) or fire hydrant while observing conveyances and measuring water level in the BMP. Such testing not only confirms that conveyances to the BMP are functioning properly but also helps to confirm the size of the CDA (i.e., that site grading is correct) and that sub-drain systems are functioning properly. Use of fire hydrants as a source of water requires prior notice be provided to the fire department, a means of metering how much water is used (e.g., a magnetic flow meter), and a water taking permit from the municipality, including payment for the volume of water used. An example of a simulated storm event test design to confirm that conveyances are functioning properly for a hypothetical infiltration trench is provided in Section 8.5.1.

Natural or simulated storm event testing can also be undertaken to confirm that an LID BMP drains at an acceptable rate. Designing such tests is much more involved and requires the deployment of specialized field monitoring equipment like continuous water level loggers (i.e., pressure transducers) in monitoring wells, flow measurement apparatuses (e.g., area-velocity sensors) in sub-drain or outlet pipes and rain gauges, in addition to staff familiar with the use and calibration of such equipment and the processing and analysis of the data. Section 8.6 provides guidance on the utility and design of continuous monitoring programs along with key references for further reading. In many cases, testing to determine the drainage rate of a BMP is most easily done through continuous monitoring during natural storm events.

<u>For stormwater infiltration BMPs (i.e., bioretention and dry swales, permeable pavements, underground infiltration systems) it is recommended that natural storm event testing be undertaken in conjunction with continuous monitoring of BMP water level, outflow and rainfall depth at the site as part of Assumption and Verification inspections to evaluate the drainage rate (see Section 8.6).</u> Simulated storm event testing can be undertaken to evaluate the drainage rate of small infiltration BMPs such as rain gardens, permeable driveways, soakaways or small infiltration trenches (i.e., 50 m^2 in surface area or less). However, for larger BMPs like dry swales, permeable pavements and

underground infiltration chamber systems, the quantity of water needed for such testing often makes simulated storm event testing not feasible or requires use of a fire hydrant as the water source.

Figure 8.21: *Simulated storm event testing of a dry swale with a water truck.*

8.5.1 Test Methods, Equipment and Triggers for Corrective Action

If the primary objective of natural or simulated storm event testing is only to confirm that conveyances are delivering stormwater to the BMP, this is easily done by observing where water flows as it is delivered to the CDA. Prior to and after the release of water, measurements of water level in monitoring wells should be made and recorded to be able to detect whether or not flows are reaching the water storage portion of the BMP if it cannot be observed visually. Manual water levels measurements can be taken by lowering a rod, level tape or string with a weight on the end into the well until the bottom is reached and measuring the height of water present from the maximum water level indicated on the device. Water level can also be measured using a pressure transducer installed to just above the bottom of the well and set to continuously record water level at 1 minute intervals (see Section 8.6). For BMPs that contain sub-drains that can be accessed and visually inspected, observations should be made to determine if flow from the sub-drain pipe occurs following delivery of water to the BMP.

For simulated storm event testing, knowledge of the water storage capacity of the BMP, approximate infiltration rate of the native subsoil, and maximum flow rate of the water source is needed to design the test. If the BMP contains a sub-drain that can be accessed and visually inspected, observation of flow from the sub-drain pipe is enough to confirm water has been received and that the sub-drain is functioning properly. If no sub-drain is present and only monitoring wells are available to detect if flow is reaching the water storage portion of the BMP, calculations prior to testing are needed to determine the quantity of water needed for the test. Enough water should be available to raise water level in the water storage portion of the BMP by at least 2 cm in order to reliably detect change in water level through monitoring well depth measurements. An example test design is described below.

An underground infiltration trench with no sub-drain has been constructed that receives parking lot runoff via a catchbasin and leader pipe connected to the trench. The property owner or their consultant wishes to confirm the trench receives runoff from the parking lot drainage area through simulated storm event testing. The trench footprint surface area (SA) is 30 m^2 and is filled with clear ¾" diameter clear stone with an assumed porosity (p) of 40%. A monitoring well is installed with the well screened within the sub-surface water storage reservoir (i.e., bottom elevation of the trench).

The approximate infiltration rate of the underlying sandy clay loam subsoil is 25 mm/h. It is proposed that a water tanker truck be used as the water source, with a capacity of 13.0 m^3 and maximum flow rate (f) of 4.5 L/s (0.0045 m^3/s). The following calculation can be used to estimate the total volume of water (V) needed to register a 2 cm (0.2 m) change in water level reading in the monitoring well:

V = (Vs + Vi) + (Vs + Vi) * 0.1

where,
Vs = Volume to be stored
Vs = SA * 0.2 m * p
Vs = 30 m^2 * 0.2 m * 0.4
Vs = 2.4 m^3

and,
Vi = Volume infiltrated during the test (approximate)
Vi = Vs/(f * 3600) * i/(1000*p) * SA
Vi = 2.4 m^3/(0.0045 m^3/s * 3600 s/h) * 25 mm/h/(1000 mm/m * 0.4) * 30 m^2
Vi = 0.28 m^3

and,
0.1 = estimated abstraction ratio to account for water loss by evaporation and retention on the parking lot surface and clear stone fill material (i.e., 10% loss)

Therefore,
Vt = (2.4 m^3 + 0.28 m^3) + (2.4 m^3 + 0.28 m^3) * 0.1 = 2.95 m^3

So assuming that about 10% of the water delivered to the parking lot will be lost to evaporation and retention, 2.95 m^3 or about 3.0 m^3 (3,000 L) of water needs to be delivered to the BMP (i.e., releasing water at the maximum flow rate of 4.5 L/s for about 11 minutes) in order to register a 2 cm increase in water level in the 30 m^2 infiltration trench.

Equipment needed for natural or simulated storm event testing will vary depending on the BMP type, objectives of testing and the chosen method but can include the following:

- Water source of sufficient quantity (e.g., water truck, fire hydrant, truck mounted cistern)
- Safety apparel (steel toed boots)

- Safety cones or barriers (for restricting access when testing permeable pavements)
- Clipboard, inspection field data forms, pens
- Camera
- Water level tape or dip stick
- Measuring tape
- Surface ponding well (e.g., Figure 8.18)
- Sub-surface water storage reservoir monitoring well (e.g., Figure 7.1, 7.4 and Figure 7.5)
- Pressure transducers data logger (optional ,for detecting water level change in sub-drains)
- Hydrant coupling kit (for connecting to fire hydrant)
- Magnetic flow meter and data logger (for measuring quantity of water delivered to the BMP)
- Pipes (to distribute flow to the CDA or BMP itself)
- Pipe couplings (to connect water truck or fire hydrant hose/nozzle to flow meter and distribution pipes);
- Pick for opening manholes or catchbasin grates;
- Multi-gas sensor (for safe access of manholes or catchbasins);

Acceptance criteria for LID BMP drainage performance for both natural and simulated storm event testing are as follows:

1. Water flows into the BMP as intended;
2. For bioretention, dry swales and enhanced swales, the surface water storage reservoir (i.e., surface ponding) fully drains within 24 hours of the end of the storm;
3. For bioretention and dry swales, the filter bed surface infiltration rate ≥25 mm/h and ≤203 mm/h, or consult manufacturer or vendor for an acceptable range specific to the filter media product.
4. For enhanced swales, vegetated filter strips and soil amendment areas, the surface infiltration rate ≥15 mm/h and ≤203 mm/h, or consult manufacturer or vendor for an acceptable range specific to the topsoil product.
5. For newly constructed BMPs (i.e., Assumption inspection), the active sub-surface water storage reservoir volume drains within 48 to 72 hours of the end of the storm and sub-drain peak flow rate is within +/- 15% of design specification; and
6. For aged BMPs (i.e., Performance Verification inspections), active sub-surface water storage reservoir volume drains within 48 to 96 hours of the end of the storm and sub-drain peak flow rate is within +/- 15% of design specification.

<u>If through natural or simulated storm event testing it is observed that any of the above drainage performance criteria applicable to the BMP are not met, corrective actions are necessary. In an Assumption inspection of a new BMP, unacceptable test results indicate the need for FIT work or consultation with the designer to determine what portions of the BMP needs to be rehabilitated or reconstructed</u>. Depending on the nature of the problem, corrective actions may involve re-grading the CDA or inlets or unclogging or reinstalling obstructed inlets or pipes.

A drainage rate of less than 48 hours indicates that the sub-drain pipe or orifice may be oversized and that a flow restrictor should be added, or that the flow restrictor valve can be adjusted to a more restrictive setting.

<u>In a Performance Verification inspection of an aged BMP, longer than acceptable drainage time results indicate the need to rehabilitate, reconstruct or replace part or all of the BMP and should trigger the planning of such work</u>.

The time required to fully drain the surface and sub-surface water storage reservoirs can be determined directly from continuous monitoring by repeated manual water level measurements or the use of a water level logger. For infiltration BMPs, calculations of sub-surface storage reservoir drainage rate should be based on a drainage time observation over a set water level interval (e.g., between one half to one quarter full) to reduce systematic error associated with the estimation method and better enable examination of trends over time as the BMP ages (see Inspection Field Data Forms in Appendix C).

For bioretention cells and planters, it is recommended to calculate filter bed surface infiltration rate (i.e., surface water storage reservoir drainage rate) using surface ponding well data based on the time required to drain the last 50 mm of ponded water as a conservative estimate (see Section 8.4 and Bioretention and Dry Swales Inspection Field Data Form in Appendix C).

8.6 Continuous Monitoring

Continuous monitoring is the most comprehensive approach to inspection of stormwater BMPs that can provide quantitative information about drainage and water treatment performance during actual storm events, which can be directly compared to design specifications and regulatory criteria to determine if it is functioning and performing as intended. When it is conducted during natural storm events it involves deployment of specialized monitoring equipment at the BMP site for 6 months to two years, routine visits to download and maintain the equipment and statistical analyses of the monitoring data, all of which needs to be performed by skilled individuals trained in a variety of environmental monitoring techniques. When conducted during a simulated storm event it involves deployment of monitoring equipment at the BMP site for about 3 to 5 days and analysis of the monitoring data. Continuous monitoring is the most costly and time-consuming approach to inspection, but warranted in certain situations.

At a minimum, continuous monitoring should be undertaken as part of Assumption and Verification inspections in the following situations:

1. For infiltration BMPs designed without sub-drains to determine active sub-surface water storage reservoir volume drainage time and filter bed surface infiltration rate.

2. For infiltration BMPs designed with flow-restricted sub-drains, to determine sub-drain peak flow rate, active sub-surface water storage reservoir volume drainage time and filter bed surface infiltration rate.
3. As part of Forensic inspection and Testing (FIT) work to determine corrective actions for suspected problems with drainage or effluent quality detected through other inspection and testing work.
4. When little information is available about the effectiveness of a certain type of BMP in a certain environmental context, or when a new technology is being implemented for the first time in a certain context or geographic region.
5. Where the sensitivity of the receiving water warrants a high level of inspection and testing to determine if BMP effluent quality meets design specifications or regulatory criteria.

Continuous monitoring is also recommended for infiltration BMPs with unrestricted sub-drains to determine if drainage performance meets design specifications or regulatory criteria, to provide the information needed to evaluate groundwater recharge performance over time and to determine when rehabilitative action or replacement is needed.

Continuous monitoring can be performed during natural storm events by measuring rainfall depth, rate and volume of flow into and out of the BMP (where feasible) over entire events and, if water treatment performance is to be assessed, collecting water samples to determine event mean pollutant concentrations and loads in effluent from the BMP. To assess drainage performance (i.e., sub-drain peak flow rate, drainage time; surface infiltration rate) by continuous monitoring, the inflows and outflows must be measured or estimated along with continuous measurement of water level in the water storage portion(s) of the BMP (i.e., both surface and sub-drain storage). Where inflow to the BMP cannot be measured (e.g., BMP receives inflow as sheet flow or via multiple inlets) it is possible to estimate inflow volume based on event rainfall depth and the size and runoff coefficient of the CDA. Water treatment performance (i.e., pollutant removal efficiency ratios) can be evaluated through automated sampling of inflow and outflow and laboratory testing of flow-weighted composite water samples to determine event mean pollutant concentrations and loads. If sampling inflow to the BMP is not feasible, simultaneous sampling of flow from a nearby untreated drainage area is also necessary to calculate pollutant removal efficiency ratios by comparing outflows from the BMP to those from the untreated drainage area.

Continuous monitoring can also be performed to evaluate drainage performance during a simulated storm event test by directing a known quantity of clean water to the BMP using either a water tanker truck or fire hydrant and measuring water level change in the water storage reservoirs (i.e., surface and sub-surface) of the BMP along with the rate of outflow from the sub-drain. While it is possible to evaluate water treatment performance of a BMP through continuous monitoring during a simulated storm event test, it requires dosing the water source used with a known quantity of the pollutant of concern which is not feasible in most cases.

Design of the continuous monitoring program will depend on what parameters are relevant to the BMP being inspected and the objectives of the inspection work. <u>As part of Assumption and</u>

Verification inspections, it is recommended that continuous monitoring be conducted to determine if the drainage performance of the infiltration BMP meets design specifications or regulatory criteria. When included as part of Assumption inspection work, in addition to determining if the BMP is functioning as intended prior to acceptance, such inspection work provides a baseline of information to which subsequent monitoring (e.g., as part of Verification inspections) can be compared, to evaluate how performance changes over the routine operation of the facility and determine when the facility needs rehabilitation or replacement (i.e., the end of its lifespan). Drainage performance evaluation work should determine the time required for the BMP to fully drain runoff from a storm event that produces enough runoff to completely fill the sub-surface water storage reservoir of the BMP or between 15 and 25 mm depth over the CDA.

Evaluation of the water treatment performance can be included in program design, but it will greatly increase the cost of the work and length of the monitoring period required to produce meaningful results. Continuous monitoring to evaluate water treatment performance should be undertaken when the BMP is a new or hybrid technology for which little or no treatment performance evaluation results are available or where the sensitivity of the receiving water warrants a high level of inspection and testing to confirm that regulatory criteria are being met.

Some general guidance and tips on the design of continuous monitoring programs to evaluate drainage and water treatment performance of LID BMPs are provided in the following section along suggestions for the types of equipment that may be needed.

Recommended sources of in-depth guidance on monitoring the performance of stormwater BMPs, aimed at assisting stormwater infrastructure asset managers with understanding basic concepts and key considerations regarding program design and implementation are as follows:

- Optimizing Stormwater Treatment Practices: A Handbook of Assessment and Maintenance (Erickson et al., 2013);
- Technical Guidance Manual for Evaluating Emerging Stormwater Treatment Technologies (Washington State Department of Ecology, 2011);
- Urban Stormwater BMP Performance Monitoring (Geosyntec Engineers and Wright Water Engineers, 2009);
- Center for Watershed Protection, Managing Stormwater Post-Construction Guide, BMP Performance Verification Tool (Tool 8) Appendix A (CWP, 2008);

Detailed standard operating procedures for conducting continuous water level monitoring and simulated storm event testing (i.e., simulated runoff testing) to evaluate BMP drainage performance are available in the City of Philadelphia's Green Cities, Clean Waters Comprehensive Monitoring Plan, Appendices C and D (City of Philadelphia, 2014).

8.6.1 Program Design and Equipment

Drainage Performance Evaluations

It is recommended that at a minimum, the drainage performance of stormwater infiltration BMPs be evaluated as part of Assumption and Verification inspections. Drainage performance, or the ability of the BMP to fully drain runoff from a certain size storm event within a certain time period, can be evaluated by continuous monitoring during natural or simulated storm events. Compared to simulated storm event testing, continuous monitoring over natural storm events provides the advantage of collecting data over a broader range of storm events (i.e., depth and intensity), and antecedent conditions (e.g., soil moisture, temperature), but requires longer durations of field monitoring in order to capture the targeted storm event size. When a water source of sufficient size to fill the sub-surface water storage reservoir is available, it is recommended that drainage performance evaluations be performed by simulated storm event testing as results can be produced within a much shorter time period (e.g., within a week) as opposed to natural storm event testing, which can require field monitoring activities over 6 months to 2 years in duration.

The general approach involves installing water level logger sensors (i.e., pressure transducers) in:

- a perforated standpipe on the BMP surface to measure the time required to drain water ponded on the surface (i.e., the surface water storage reservoir component) and estimate filter bed surface infiltration rate; and,
- a monitoring well screened within the sub-surface water storage reservoir component of the BMP.

The water level logger sensor should be installed such that it is slightly elevated off the bottom of the well (Figure 8.22). A rain gauge (e.g., tipping bucket rain gauge) and barometer (i.e., pressure transducer) are also needed within 2 kilometres of the BMP site. It is often best to install the barometer in the same monitoring well as the water level logger. The water level loggers, barometer and rain gauge should be programmed to record at 5 minute intervals. Water level readings in the BMP are made manually at the time of deployment in order to establish the vertical correction offset between sensor water level readings and the elevation reference, typically the top of the well. Rainfall depth, and water level logger data (pressure and temperature) are downloaded at regular intervals via a laptop computer. Water level logger data must be compensated for changes in barometric pressure using simultaneously logged data from the barometer prior to analysis. Manual water level readings are taken when downloading data and re-deploying sensors in order to calibrate water level readings and determine whether sensor drift occurred during the deployment.

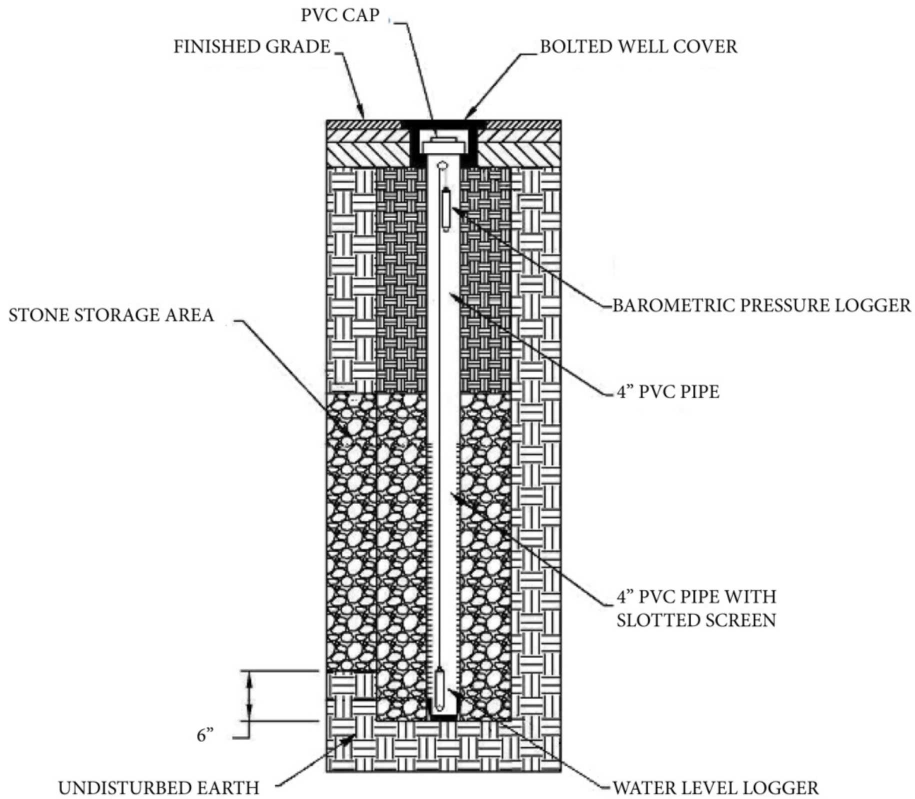


Figure 8.22: *Diagram of a typical water level logger installation in an infiltration BMP sub-surface water storage reservoir monitoring well (City of Philadelphia, 2014).*

For infiltration BMPs with no sub-drains, continuous monitoring to evaluate drainage performance should capture the full drainage period for at least one rain event large enough to fill the sub-surface water storage reservoir or at least 3 rain events between 15 and 25 mm in depth. Mean values for surface and sub-surface water storage reservoir drainage times and rates should be calculated and compared to design specifications or regulatory criteria to determine if the BMP is draining at an acceptable rate. Alternatively, a simulated storm event test can be performed, that involves directing enough water to completely fill the sub-surface water storage reservoir and monitoring decline in water level over time until the BMP is completely drained. Such a test should be timed to coincide when no rain is in the forecast for at least 4 days.

For infiltration BMPs designed with flow-restricted sub-drains to meet peak flow reduction/erosion control regulatory criteria, additional monitoring equipment is needed. In addition to a rain gauge, barometer, and water level loggers, a flow measurement apparatus needs to be installed in the sub-drain outlet pipe to monitor flow rate. Choice of flow measurement equipment will depend on the size and configuration of the pipe. Area-velocity sensors use water level and flow velocity measurements in conjunction with knowledge of the pipe size to produce measurements of flow rate. Magnetic flow meters can also be used to measure flow in full pipes with knowledge of the pipe size.

Alternatively, a tipping bucket flow gauge can be installed at the sub-drain pipe outlet that has the capacity to measure the expected maximum flow rate from the sub-drain pipe. Flow rate data produced by such instruments can be directly compared to design specifications and regulatory criteria to determine if the BMP is providing the intended level of peak flow control.

For infiltration BMP designed with flow-restricted sub-drains, continuous monitoring to evaluate drainage performance should be performed by conducting a simulated storm event test using the following stepwise procedure:

<u>Simulated storm event test procedure for evaluating drainage performance of infiltration BMPs</u>

1. Select a date for the test when no rainfall is forecast for at least 3 days.
2. Install flow monitoring apparatus downstream of the sub-drain flow restrictor device.
3. Temporarily plug the sub-drain pipe.
4. Direct enough water to the BMP to completely fill the sub-surface water storage reservoir.
5. Remove the sub-drain plug.
6. Allow the BMP to fully drain.
7. Determine the maximum flow rate from the sub-drain from flow measurements
8. Determine the drainage time from the water level measurements
9. Calculate the infiltration rate based on water level measurements once flow from the sub-drain has stopped as the change in storage volume over time divided by the infiltration area.

As mentioned in the previous section, to design a simulated storm event test, knowledge of the surface and sub-surface water storage capacity of the BMP is needed to determine the quantity of water needed, which will determine how the water will need to be delivered. If more than 13 m^3 of water (i.e., the typical capacity of water tanker trucks) is needed to fill the sub-surface water storage reservoir, a fire hydrant will need to be used as the water source.
The values obtained for maximum outflow rate from the sub-drain, drainage time and infiltration rate should be compared to design specifications or regulatory criteria to determine if the BMP drains at an acceptable rate.

For infiltration BMPs that contain unrestricted sub-drains, continuous monitoring to evaluate drainage performance should capture the full drainage periods for at least one storm event large enough to completely fill the sub-surface water storage reservoir to the elevation of the sub-drain pipe invert or at least 3 rain events between 15 and 25 mm in depth. Mean values for drainage time and infiltration rate should be calculated and compared to design specifications or regulatory criteria to determine if the BMP is draining at an acceptable rate. Alternatively, a simulated storm event test can be performed, using the stepwise procedure described above.

When continuous monitoring during natural storm events is the chosen approach to inspection, the site should be visited once every two weeks to ensure that all equipment remains functional and to download instruments and check on/replace batteries.

Water Treatment Performance Evaluations

When the objectives of BMP inspection include determining if the BMP is providing a minimum level of water treatment performance, design of the continuous monitoring program needs considerable thought. Table 8.10 describes some key considerations in program design.

When deciding if continuous monitoring to evaluate water treatment performance is to be part of Assumption and Verification inspections, it is important to consider budgetary constraints as such work typically involves having monitoring equipment deployed for 6 months to 2 years along with the costs associated with routine site visits (every two weeks), quality assurance checking of data, statistical analyses of results and staff training. Continuous monitoring must be performed by skilled individuals trained in a variety of environmental monitoring techniques and, in many cases, with confined space entry training and equipped with certified and recently calibrated safety equipment (i.e., tripod, winch, harnesses, multi-gas detectors).

A typical continuous monitoring program to evaluate water treatment performance is conducted between April and November, as water sampling during freezing winter temperatures is often difficult or not feasible. To evaluate BMPs that only produce outflow during large storm events (e.g., 15 mm depth or more), monitoring work should begin in the spring and continue through the summer as these months tend to be the wettest of the year. Rainfall depth should be continuously monitored within 3 kilometres of the BMP location and ideally, at more than one location. Storm events sampled should represent a range of conditions with respect to rainfall depth and intensity. Dry periods of 3 hours or greater should be used to define the beginning and end of storm events. A minimum of ten (10) equal-volume samples (i.e., aliquots) should be collected during each storm event. To adequately characterize variability in BMP water treatment performance, laboratory test results from a minimum of fifteen (15) storm events should be obtained. The evaluation period should also include at least one routine maintenance cycle (e.g., cleaning of inlets and pretreatment devices) to capture any variability in water treatment performance of the BMP over this time period.

Table 8.10: *Key considerations in designing continuous monitoring programs for water treatment evaluation.*

Variable	Key Considerations	Recommendations
BMP water storage capacity	Many LID BMPs contain sub-drains that only flow during large storm events which will limit the number of events that produce water samples in a given year.	Focus on BMPs that generate outflow during storm events of 25 mm depth or less. Budget for continuous monitoring periods of 6 months to 2 years to capture samples from enough storm events to produce meaningful results (at least 15) with site visits every 2 weeks to check on equipment and download and QA/QC check data.
Inlet configuration	Measuring and sampling inflow is often not feasible for BMPs that receive sheet flow or have multiple inlets.	Parallel measurement and sampling of outflow from a nearby, untreated drainage area is needed to evaluate water treatment performance of BMPs where inlet monitoring is not feasible.

Storm event size and duration	To adequately characterize water treatment performance, monitoring results from a range of storm event sizes is needed which requires that the programming of automated water samplers should be capable of capturing flow from a range of storm event depths and durations.	Start with collecting 500 mL aliquots every 10 minutes after flow is initiated. For an automated water sampler that contains 24 one litre bottles, this allows sampling over an 8 hour period. Sampling frequency should be adjusted to optimize between filling all the bottles in the sampler with capturing as much of the period of flow as possible. Alternatively, automated samplers can be coupled with flow measurement apparatuses to alter sampling frequency as flow rate changes.
Flow-weighted sampling method	How individual water samples are combined to produce the composite sample for laboratory testing will greatly affect results.	Composite samples should be generated by examining flow rate over the period each sample was taken, calculating what proportion of the total flow during the event that represents, and using this relationship to measure the quantity taken from each sample bottle to produce the composite sample.
Water quality parameters of interest	The cost of laboratory testing of water samples increases with the number of parameters to be tested. Water treatment performance evaluations should focus on the parameters of greatest concern from regulatory or receiving water sensitivity perspectives.	As most pollutants common to urban stormwater runoff are associated with suspended solids, focus on evaluating Total Suspended Solids removal efficiency. For nutrient-limited receiving waters, add nutrient testing (Total Phosphorus and Phosphate, Total Nitrogen, Nitrate and Nitrite). For bacteria-limited receiving waters add bacteria testing. When bacteria removal performance is to be evaluated, samples must be submitted for laboratory testing within 48 hours of the end of the storm event or refrigerated samplers are needed.
Security of monitoring equipment	In some cases, monitoring equipment will need to be installed at the ground surface, and require means of preventing tampering or sabotage.	House automated water samplers in protective structures that are securely locked and inaccessible or in manholes where possible.
Confined space entry	Installing and checking flow monitoring and sampling equipment often requires entry into confined spaces.	Monitoring that involves confined space entry requires adequately trained staff equipped with certified and recently calibrated safety equipment.

The choice of what water quality parameters are to be evaluated will depend on the objectives of the work but typically include one or more of the following: total suspended solids, nutrients (total phosphorus, orthophosphate, total nitrogen, nitrate, nitrite), metals, pH, chloride, conductivity, oil and grease, turbidity and PAHs. Bacteria (e.g., *E.Coli* or total coliforms) can also be evaluated but requires that samples be laboratory tested within 48 hours of being collected, which means samples need to be submitted for testing soon after the end of the storm event or that refrigerated auto sampler units be used.

Whenever water treatment performance is being evaluated, proper handling and storage of water samples is essential to prevent contamination and produce representative samples and accurate laboratory test results. Prior to sampling, bottles must be cleaned with phosphate-free detergents and rinsed with acid. Samples submitted for metals testing should be preserved with nitric acid. Samples submitted for bacteria testing should be contained in sterile bottles provided by the analytical laboratory and refrigerated immediately after collection and during transport to the laboratory.

Testing of water samples must be done by an accredited analytical laboratory. A list of accredited analytical water testing laboratories in Ontario is provided in Appendix B.

Interim results from such continuous monitoring work should be peer-reviewed before being used to trigger any corrective actions and final results should be made available to the stormwater management practitioner and research community to help foster continuous improvement of BMP designs and understanding of their effectiveness. Ideally, results from such work should be suitable for inclusion in the International Stormwater BMP Database. Information about the database and detailed guidance on standards for reporting stormwater BMP performance results is provided on the project website (www.bmpdatabase.org).

8.7 Green Roof Irrigation System Testing

In dry or temperate climates, an irrigation system can be crucial for establishing and maintaining green roofs. Extensive green roofs planted with drought tolerant plants do not always need an irrigation system, but intensive green roofs planted with a wider variety of plants would not be able survive without one. Most green roofs will require supplemental water either to enhance or speed up the establishment process or to protect the plantings during times of sustained drought. This can be accomplished by hand watering or installing an automated irrigation system.

Irrigation systems vary greatly in level of complexity. They can be simple hand watering systems using hose bibs on the roof and manual sprayers, or installed automated systems that are activated by timers, or more sophisticated “smart irrigation” systems that can be remotely controlled and coupled with rain sensors or sources of local weather data to only operate during extended dry periods (i.e., droughts). Drip irrigation is the most common type of irrigation system for green roofs (Green Roof for Healthy Cities, 2011) because it transfers the water directly to the growing medium via drip emitters installed at or near the surface with relatively little loss to evaporation. Other types of irrigation systems use handheld or installed spray nozzles to distribute water to the plants.

If an automatic irrigation system is in place, individuals performing inspection testing, maintenance and repairs on it should refer to the operator's manual from the product vendor or installer for instructions specific to that product.

Regardless of the type of irrigation system installed, it should be regularly inspected and tested to ensure it is free of damage and functioning properly. Such testing should be done annually in the spring as part of reconnecting the system to the water supply after having been disconnected and blown dry for the winter (see Section 7.6.5, Table 7.35 for guidance on spring start-up and winterization of green roof irrigation systems).

A green roof irrigation system test involves inspecting the supply lines, fittings and distribution points (e.g., drip emitters or spray heads) while the system is running to check for leaking, damaged, obstructed or misaligned components and dry or saturated portions of the filter bed/growing medium. A leaking or damaged supply line will often wash out or saturate a small area. An obstructed drip emitter or spray nozzle will create dry spots. If visual assessments of vegetation cover and condition reveal locations where plantings have died or are not thriving, make sure it is not due to irrigation system malfunction or damage.

Green roof irrigation system testing also provides a means of confirming that the drainage system is functioning properly. If the irrigation system test results in ponding on the filter bed/growing medium surface or in/around overflow outlets, repair or routine maintenance of those components may be necessary.

8.8 Green Roof Leak Detection Testing

On buildings featuring a green roof, a waterproofing membrane layer that covers the whole roof is essential to prevent water damage to the building. In some cases, a root barrier layer is also a part of the green roof design that protects the waterproofing membrane from being penetrated by roots and degraded by soil microbial activity. On top of these protective layers are the water retention and drainage layer, filter cloth, growing media and plants, making it impossible to visually inspect them for damage or leaks. There are two main approaches to leak detection for green roofs – flood tests and low-voltage leak detection tests.

Flood tests for detection of green roof leaks can be conducted as part of Construction inspections, prior to planting. The test requires an experienced professional to narrow down a small area where the leak may be originating from. The suspected area is isolated from the rest of the roof, the roof drains are plugged, 10 cm of water depth is introduced and observations are made. Once the leak is found, the area is opened up and the waterproofing membrane is repaired. This process is time-consuming and costly, as the leak is not always found during the first round of patch flooding (US GSA, 2011).

The low-voltage leak detection test utilizes electricity to locate water penetrations through the waterproofing membrane. Such leak detection systems can also be referred to as Electric Field Vector Mapping (EFVM®) systems. They require a grounded, conductive material be directly below the waterproofing membrane, such as reinforced concrete or metal, and that the membrane be a non-conductive material. During roof construction and prior to green roof installation, a conductive wire is looped around the surface of the waterproofing membrane and connected to an impulse generator. Testing involves the inspector or leak detection technician introducing a low-voltage, pulsating electric charge onto the surface of the waterproofing membrane which should be moist at the time. A watertight membrane will isolate the potential difference between the wetted surface and the underlying grounded conductive material layer, while breaches in the membrane will cause an electrical connection to occur. The inspector or leak detection technician reads the directional flow of current with a potentiometer to locate the point of entry with pinpoint accuracy. Low-voltage leak detection tests can be performed before and after a green roof is installed. As such, the location of leaks can be very precisely located and repaired with minimal disturbance to the rest of the roof (US GSA, 2011).

It is important to test green roofs for leaks as part of Construction, Assumption and Verification inspections. As part of Construction inspections, testing confirms that the roof layers have been installed correctly and that it is ready for planting. As part of Assumption inspections it helps determine if the green roof is ready to be assumed by the property owner/manager/municipality. Tests may also be done as part of Verification inspections (i.e., every five years) to check for leaks, and as part of FIT work to locate and repair leaks discovered through visual inspection work.

8.9 Cistern Pump Testing

Most rainwater cisterns are placed in basements or outdoors, and require a pump to distribute the water to service its designated locations throughout the property, generally located at higher elevations. Typically, a pump is arranged with a pressure tank, which includes a centrifugal pump that draws the water out of the storage tank and into the pressure tank, where it is stored and ready for distribution. As part of this distribution system, an appropriately sized pump is required to produce a sufficient flow to efficiently transport water that feeds into the pressure tank. With prolonged usage, the pump capacity may decline, which would be reflected by a reduction in flow rate. A simple flow rate measurement using a bucket, stopwatch and volume measurement device (e.g., graduated cylinder) at the outlet location can reveal whether the pump is functioning. Once the flow rate is measured the value can be compared to the design flow rate. If the pump is not creating sufficient pressure, then the flow rate will be inadequate. If the flow rate is below the design specification, servicing of the pump by a skilled technician should be scheduled.

In addition to confirming that the pump is functioning and checking on the flow rate, routinely conducting cistern pump tests also provides the opportunity to visually inspect the water produced by the system. If the water delivered from the cistern is discoloured or highly turbid (i.e., murky), it indicates that the pretreatment device or filtration system is malfunctioning or needs maintenance.