Green Infrastructure Performance Assessment

December 2019

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ACRONYMS/ABBREVIATIONS

Acronyms/Abbreviations	Definition
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
AV	Area-Velocity
BMP	Best Management Practice
CBD	Central Business District
CN	Curve Number
EGLE	Environment, Great Lakes & Energy *(formerly MDEQ)*
ET	Evapotranspiration
FHWA	Federal Highways Administration
GI	Green Infrastructure
GIS	Geographic Information System
I/I	Infiltration and Inflow
MDEQ	Michigan Department of Environmental Quality *(now, EGLE)*
MSU	Michigan State University
MTD	Manufactured Treatment Device
NRCS	Natural Resource Conservation Service
QAPP	Quality Assurance Project Plan
ROW	Right-of-Way
RR	Railroad
SEMCOG	Southeast Michigan Council of Governments
SPAW	Soil Plant Air Water
SPNL	Soil Plant Nutrient Library
SWMM	Stormwater Management Model
USDA	United States Department of Agriculture

1.0 INTRODUCTION

Green infrastructure (GI) is increasingly used to manage stormwater runoff with the goal of mimicking natural hydrology, improving receiving water quality, and reducing flooding. GI is typically designed to capture or treat specific volumes and peak flow rates of stormwater runoff. To verify the effectiveness of GI in meeting these requirements and to improve design and construction techniques, monitoring of the facilities is recommended.

The purpose of this document is to help identify ideas and methods to assess the performance of GI practices. This document focuses on hydrologic issues and contains information on both quick assessment techniques and long-term monitoring. The following information is covered in this document.

> *Section 1* talks in general terms about developing and implementing a monitoring plan. Information is provided on managing data and ideas to consider for monitoring during the design phase of the GI practice.
>
> *Section 2* discusses the importance of understanding the tributary drainage area, or watershed, draining to a GI practice and how to characterize the information.
>
> *Section 3* focuses on the big picture issues and commonly asked questions associated with the performance of a GI practice. For example, what is the overall runoff volume reduction due to the presence of the GI practice.
>
> *Section 4* dives into more details by considering how to assess each component of a GI practice. For example, how to look at the inlet efficiency of a curb cut and how to measure the infiltration rate through a porous pavement system.
>
> *Section 5* talks about the equipment used to measure rainfall and flow. This section walks through primary devices, like weirs and flumes, as well as the metering equipment, such as pressure transducers and area-velocity meters.

1.1 DEVELOPING A MONITORING PLAN

Performance assessment studies begin by developing a thorough plan for the work. Ideally, monitoring plans are developed during the design phase of a project. Developing a monitoring plan begins by defining the study objectives. The first step is to identify what specific questions are targeted for answers. The problem and questions guide the creation of the study. After clearly defining the study objectives the next step is to work through how the data will be acquired. The data acquisition includes the field data to be collected and other data sources that will be used as part of the study. Planning the data acquisition needs to get into the details such as where will the monitoring equipment be installed, what equipment will be used, what time period will it record, and what time increment will be used to record data. Site visits and preliminary hydrologic calculations are often required to screen good monitoring sites and identify the anticipated flow range for the equipment to monitor. Another key aspect of the data acquisition is to identify how the monitoring equipment will be calibrated and what steps will be taken to validate and verify the monitoring data. The next step is to work through how the data will be analyzed. Think through and describe what tools and techniques will be used to store, calibrate, verify, analyze and interpret the data. This also includes identifying statistical tests that will be used to show statistical significance.

The monitoring plan should be documented in the form of a Quality Assurance Project Plan (QAPP). The study objectives, design, data acquisition and data analysis should all be

> ***Data Quality Indicators***
>
> *Precision* – the degree of agreement among repeated measurement of the same characteristic.
>
> *Accuracy* – measure how close your results are to a true or expected value.
>
> *Representativeness* – the extent to which measurements represent the true environmental condition.
>
> *Completeness* – the comparison between the amount of valid, or usable, data you originally planned to collect, versus how much you collected.
>
> *Comparability* – the extent to which data can be compared between sample locations or periods of time.

documented along with identifying responsible parties for the difference work phases. A suggested outline for the QAPP is:

1. Background *(description of overall project the monitoring is supporting)*
2. Objective
    - 2.1. Problem Definition
    - 2.2. Study Objectives
    - 2.3. Data Quality Objectives for Measurement Data
    - 2.4. Training Requirements/Certifications
    - 2.5. Documentation and Records
3. Contact Information and Responsible Parties
4. Preliminary Analysis
    - 4.1. Site Description
    - 4.2. Design and Construction Understanding
    - 4.3. Estimated Hydrologic Calculations
5. Measurement/Data Acquisition
    - 5.1. Data Sources
    - 5.2. Instrument/Equipment Testing, Inspection, Calibration and Maintenance
    - 5.3. Monitoring Procedures
    - 5.4. Schedule and Frequency
    - 5.5. Data Management
6. Data Analysis
    - 6.1. Data Review, Validation, and Verification
    - 6.2. Assessments and Response Actions
    - 6.3. Analysis

1.2 IMPLEMENTATION OF MONITORING PLAN

Proper implementation of a monitoring plan is as important as a well-designed plan. Trained professionals should be used to install and maintain the equipment. Health and safety are always of concern and a separate health and safety plan should be developed and followed. Often equipment is installed in manholes which are confined spaces and require special training for entry.

When the equipment is installed it should be tested and calibrated. Offset measurements are often required to adjust the metered data; for example, the vertical distance a pressure transducer is installed above the invert of the flow channel. Site should be visited on a regular schedule to check the equipment, download data and refresh batteries. When checking the equipment, manual measurements should be collected, if needed, to compare against the metered data and adjustments made accordingly. Sediment, debris and other materials carried by stormwater runoff can damage or impede data collection and the equipment often requires routine cleaning.

1.3 DATA MANAGEMENT AND VALIDATION

Monitoring programs typically generate a considerable amount of information. Effective data management is important to enable efficient storage, retrieval, and transfer of monitoring data. All the raw data along with installation and maintenance records should be kept in addition to a final record set with any adjustments made. Metered data should be checked and validated. Examples of checks include looking for data outliers, meter drift over time, and comparison of flow results to standard engineering equations, e.g., Manning's equation. The frequency that metering data is outside of the equipment's operating range should also be checked. Rating curves and smoothing functions may need to be applied to the raw data. It's very important to understand (and plan for) what data is being collected over what time range. For example, is a meter reading averaged over a specific period or is it an instantaneous measurement. Another example is, does the timestamp represent the data before or after the timestamp; consider hourly rainfall data, does a 3:00 timestamp represent the rainfall from 2:01-3:00, or from 3:00 to 3:59?

1.4 DESIGN CONSIDERATIONS

Ideally the monitoring plan should be developed during the design phase of a project. When this happens, the design can be adjusted to better accommodate the monitoring equipment. Primary devices such as flumes tend to be large. It's not uncommon for a flume to be 4 feet long, thereby needing a lot of horizontal space. The system also needs to be hydraulically designed to provide the desired head loss for a primary device. Weirs on the other hand, are not as long as flumes, but may be wide to accommodate the flow and require an aerated nappe. Refer to Section 5.2.1 for more discussion on primary flow devices. Some ideas to consider during design are provided below. Refer to Section 6.0 for an example monitoring site.

- *Smooth Flow Stream*. Monitoring flow relies on smooth, gradually varied flow streams. Provide straight runs for the water upstream and downstream of the meter site. Try to avoid abrupt changes in flow direction, channel slope, elevation, and channel size. Also avoid locations where two or more flow streams join or split apart.
- *Access*. Monitoring equipment needs to be accessible and often hidden from sight. Placement in manholes is often preferred. Ideally equipment needs to be within arm's reach of the surface. Manholes are considered confined spaces and require special training to safely enter. Clean outs and observation ports are often used as points for monitoring. Ports need to be large enough to reach down inside and preferably free from abrupt changes in direction.
- *Space*. Choose oversize manholes when possible. Manholes may seem large but fitting primary flow devices can be a challenge. Outlet control structures often incorporate upturned elbows, valves and other hydraulic control devices. These systems also take up valuable space.
- *Elevation*. Sometimes the primary device like a weir requires a free downstream discharge and it's beneficial to have a little extra drop in the elevation. Sometimes there's not enough change in elevation when the incoming pipe in a manhole has the invert set at the bottom of the manhole. Other systems like flumes are typically required to be set level so elevation change is not desired.
- *Vandalism*. Vandalism is often a concern. The best strategy is often to have systems placed out-of-sight such as in a manhole. On sites with multiple monitors, sometimes its advantageous to run conduits below the ground surface connecting the various structures together. The conduits can then be used to run electrical cables for the equipment.

Figure 1 Space Constrained Meter Installation

1.5 ASSET MANAGEMENT

After a GI project is constructed, asset management information should be recorded in the City's GIS regarding the details of the GI practice. There are four major groups of information recommended to be recorded. These include: (1) core information about the GI practice, (2) information on the tributary drainage areas, (3) surface areas, or footprints, of different parts of the GI practice and (4) pipes, structures and other more traditional gray infrastructure. These are discussed in the subsequent sections. Consider building geodatabase relationships into the feature to link the information together. Manufactured treatment devices have some unique attributes keep track of, these are discussed in Section 1.5.5. Assessment of GI practices (Sections 3.0 thru 5.0) are important to track with the asset information and is discussed in Section 1.5.6.

Also consider recording the vegetation planting plans for bioretention systems. This information could be stored in GIS as specific features and attributes or referenced in other documents. Understanding the planting plan is important for both maintenance of the system and assessing the Vegetation (Section 4.5).

1.5.1 Core GI Asset Information

Core information about a GI practice is stored within the attributes of a point theme feature. The core information includes reference name and location, type of practice, the storage volumes, drainage area, ownership, and maintenance responsibility. A unique identifier for each practice provides a link to other features which provide important information. This is a point theme feature class with suggested attributes identified in Table 1.

Table 1 Core GI Feature Attributes

Field	Description
GI_ID	Unique identifier assigned to each GI practice. Key field to correlate with surface area (Section 1.5.2) and drainage area (Section 1.5.2) features.
Name	Name used to reference the GI practice
Address	Street address of practice
GI Type	Bioretention, porous pavement, constructed wetlands, green roofs, basins, etc.
GI Subtype	Further define the type of GI practice: Bioretention: basic, curb bump out, linear between curb and street, etc. Porous Pavement type: asphalt, concrete, PICP, etc.
Practice Area	Total footprint surface area (square feet) of the practice as represented when the practice is full of water. Corresponds to *GI Practice Area* feature (Section 1.5.2)
Drainage Area	Total drainage area tributary to the GI practice. Corresponds to *Total Drainage Area* feature (Section 1.5.2).
Publicly Visible	Visible to the public (Y/N)
Publicly Accessible	Accessible by the public (Y/N)
Infiltration Allowed	Does the practice allow for infiltration into the subgrade (Y/N)
Volume Surface Storage	Volume of storage on the surface. This volume only represents the available storage volume for wet weather events and does not include any permanent pool of water. This value is typically zero for porous pavement systems and water harvesting systems. Refer to Section 4.3.
Volume Soil Aggregate Storage	Volume of storage available in the soil and aggregate layers. This volume only represents the available storage volume for wet weather events and does not include any permanent pool of water. Refer to Sections 4.4 and 4.7.
Volume Vault Storage	Volume of storage contained in a vault. Vaults may be subsurface arched tubes, concrete tanks, oversized pipes, cisterns, rain barrels, etc. Basically, any manmade container. This volume only represents the available storage volume for wet weather events and does not include any permanent pool of water. Refer to Section 4.8.
Volume Total Storage	Sum of Surface Storage, Soil Aggregate Storage, and Vault Storage
Volume Permanent Pool	Volume of permanent pools of water associated with the GI practice. This volume may be displaced from wet weather runoff but does not provide detention storage.

Field	Description
Volume Retention	The volume of water forced to infiltrate or evapotranspire. This volume is typically calculated as the storage volume below the invert of the outlet pipe. The retention volume is part of the total storage volume, usually part of the soil aggregate storage. Refer to Section 3.2.2.
Volume Average Annual Retention	Estimated average annual volume of water permanently retained (i.e. infiltrated and evapotranspired). Refer to Section 3.2.2.
Volume Average Annual Managed	Estimated total volume of water (retained and detained) on an average annual basis. Refer to Section 3.2.3.
Owner Name	Owner name.
O&M Responsibility Name Aesthetics	Who's responsible for maintaining the aesthetic appearance of the practice. Example activities include as weeding, mulching, landscaping, picking up trash on the surface. Consider including additional fields or tables for agreement identifiers and applicable timeframe for the agreement.
O&M Responsibility Name Function	Who's responsible for the hydrologic function of the practice. Example activities include vacuuming pavement, cleaning sediment sumps, and fixing problems when the system is not draining properly. Consider including additional fields or tables for agreement identifiers and applicable timeframe for the agreement.
O&M Plan	Provide a link or reference information to the GI practice maintenance plan.
Construction Project ID	Reference ID for construction documents. Consider a hyperlink to saved PDF files of the construction documents.
Construction Year	When was the practice installed?
Construction Cost	What was the approximate construction cost of the practice?

1.5.2 Drainage Area Features

Design and performance of a GI practice is highly dependent on the drainage area tributary to the practice. A polygon feature class of the tributary drainage areas is suggested. Subtypes within the feature class are suggested to refine the overall drainage areas. Each feature should contain an attribute correlating to the GI practice in the core information feature.

- ***GI Practice Area***. Surface area of the GI practice. This area is defined when the GI practice is full of water, i.e. what is the maximum footprint the practice occupies. Practice area can be used to illustrate the location information for the bioretentions, porous pavement, basins features. The *GI Practice Area* is also a drainage area which is accepting precipitation falling directly onto the practice. The practice footprint should correspond to the total storage volume of the practice in the core feature attributes.
- ***Overland Drainage Area***. Contributing area where overland flow drains into the practice. Limits of polygon should match edge of *GI Practice Area* which represents the high-water footprint. There should be no overlap with the *Inlet Drainage Areas*.
- ***Inlet Drainage Area***. This is the tributary drainage area to each inlet associated with the GI practice. There may be more than one inlet drainage area for each GI practice. The inlet drainage area polygon should be correlated to a specific inlet feature. There should be no overlap with the *Overland Drainage Area* or the *GI Practice Area*.

Total Drainage Area. The *Total Drainage Area* is a combination of the *Overland Drainage Area*, the *Inlet Drainage Areas*, and the *GI Practice Area*. This represents the total contributing area draining to a GI practice.

1.5.3 Surface Area Features

These are polygon features representing different footprint areas important to the GI practice. Each polygon feature should contain an attribute correlating to a GI practice in the core information feature.

- ***Permanent Pool Area***. The footprint area should correspond to the permanent storage volume in the core feature attributes.
- ***Surface Infiltration Area***. Surface area where infiltration occurs on the ground or pavement surface.

- ***Subsurface Infiltration Area***. Footprint area where infiltration occurs into the subgrade. The subsurface infiltration area is typically less than or equal to the surface infiltration area. This area is used with the subgrade infiltration rate when accounting for the permanent retention volume in the core feature attributes.
- ***Storage Vault Area***. This is the footprint area of subgrade storage vaults. This also represents footprint areas of water harvesting practices such as cisterns, which may be above grade. Area should correspond to the vault storage volume in the core feature attributes.

1.5.4 Traditional “Gray” Stormwater Components

GI practices commonly include traditional “gray” stormwater components such as manholes, catch basins, inlets, and pipes. Traditional “gray” stormwater components associated with a GI practice should be recorded assets like any other stormwater component. That is to say, they should be recorded with the City’s existing GIS for stormwater features.

1.5.5 Manufactured Treatment Devices

A new GIS feature class should be considered for Manufactured Treatment Devices (MTDs). MTDs are prepackaged water quality units purchased and installed to provide end-of-pipe treatment. They typically are used to remove sediment, gross solids, and sometimes hydrocarbons from stormwater pipe flows. These devices are commonly either hydrodynamic separators or a filtration device. MTDs are suggested to be recorded in GIS as a point feature class with the attributes below and the attributes associated with the core GI information.

- Manufacturer. Who is the manufacturer of the device?
- Model. The specific manufacturer model that was installed.
- Rim Elevation. Rim elevation of the structure.
- Invert Elevation. Bottom invert elevation for sediment storage.
- Max Sediment Depth. Manufacturer recommended sediment depth at which the unit should be cleaned out.
- Sediment Storage Surface Area. The surface area of the sediment sump. This is needed to convert the depth of solids to a volume of solids.
- Attributes describing the presence of various appurtenances such as: screens, basket, baffles, booms, filters, hoods, etc.
- Manufacturer rated peak flow rate.

1.5.6 Performance Assessments

Performance assessment information is important to keep track of. Assessment information falls into three general categories: hydrologic impact studies, rapid assessments, and long-term monitoring.

Hydrologic impact studies are discussed in Section 3.0. These studies tend to utilize long-term monitoring data to assess overall hydrologic performance on issues such as the net volume reduction. These studies contain lots of information and results are rarely a single number. Databases tracking this information are recommended to provide links or references to the study (as a PDF) instead of trying to store all the results in the database. More than one hydrologic study may be conducted for any given GI practice. Some suggested basic information to track include:

- The GI practice involved in the study.
- Name or title of the study.
- The name of the individual, company or organization who authored the study.
- When the study was completed.
- General notes or comments regarding the study.
- Provide a link or reference information to the study.

Rapid assessments are discussed in Section 4.0 for each component of a GI practice. These assessments cover many different types of information for example, an infiltration test run in the field or determining an inlet efficiency which may involve some fieldwork and some calculations in the office. There are many ways a database can be structured to record the assessment information. The core information includes:

- The type of assessment, e.g. determining an inlet hydraulic efficiency, measurement of compaction or infiltration, or confirming proper construction of a storage zone.
- Where the assessment was conducted. This might be linked to a specific GI practice (GI_ID) for a flood test or a specific asset (like an inlet) for an inlet efficiency. The location might also be a point (latitude and longitude) for tests such as infiltration or compaction.
- The test method used which is dependent on the type of assessment. For example, inlet efficiency is determined from a flow test whereas confirming proper construction of a storage zone is accomplished by surveying the site. Some types of assessments have more than one test method for example, an infiltration test can be run using a number of different test methods on soil (Table 6) or pavement (Table 8).
- The result of the assessment along with the units (if needed).
- Basic information on when the assessment was done, who performed and checked the assessment, general comments and links to photographs or other reference documentation.

Long-term monitoring equipment is discussed in Section 5.0 and is important to keep track of what equipment is used where and for how long. Suggested information to track includes:

- The location of the equipment which is often installed in manholes or in the case of rain gauges the location is usually a point (latitude and longitude).
- The type of equipment installed, for example rain gauge (Section 5.1), primary device (Section 5.2.1) or secondary device (Section 5.2.2). Recording a unique ID for each piece of equipment is recommended and helps identify units that are not performing properly.
- The monitoring period including the installation and removal date.
- The persons or agencies responsible for installing, maintaining, and removing the equipment along with the person or agencies responsible for review and checking the data.
- Reference information on where the data is stored along with field notes and photographs.

2.0 WATERSHED CHARACTERISTICS

Understanding the tributary watershed characteristics to a given BMP is critical when evaluating performance. This is true for the flow characteristics as well as if water quality constituents are being evaluated. The watershed characteristics provide the information to predict the runoff hydrology. To begin, the drainage area must be delineated and then the various characteristics quantified. A map or illustration of the watershed area should be prepared along with tabular information on the characteristics. It is important to identify the tributary drainage area to each defined inlet along with flow entering the GI practice overland (for example in the case of porous pavement). Refer to Section 1.5.2 for suggested GIS drainage area features to identify and record.

Table 2 Watershed Characteristics

Characteristic	Description and Purpose
Total Watershed Area	This is a fundamental variable that affects the total runoff potential. Used in all hydrologic calculations.
Land Use Types	Description of what the land is used for. Helps with general hydrologic calculations and pollutant load estimates. Refer below for suggested categories for land use types.
Impervious Land Cover	Impervious land cover is useful to quantify the total impervious area within the watershed and estimate the directly connected impervious area. These variables are important when calculating hydrology with SWMM. Refer below for additional information on the impervious land cover information.
Total Length of Watershed	Used to calculate the watershed lag and time of concentration. Useful to quantify and report as the length as sheet flow, shallow concentrated flow, gutter flow, and channelized/piped flow. Useful to estimate hydraulic width per the Stormwater Management Model (SWMM)
Average Watershed Slope	Helps to estimate the watershed lag. Useful to quantify and report as overland flow, paved surface, and a total average.
Soil Complex and Hydrologic Soil Group	Used with hydrologic calculations for determining abstractions due to infiltration. GIS information is available from NRCS Web Soil Survey. Useful to categorize the soils by land use types.
Disturbed Soil Areas	Location and extent of disturbed soil areas such as construction sites and dirt driveways. Useful when evaluating sediment pretreatment systems and troubleshooting poor performance issues.
Hotspots	Location and identification of potential hot spots within the watershed such as gas stations, brownfield sites, leaky underground storage tanks, etc. Useful when considering water quality issues.
Irrigation	Location of areas with in-ground irrigation systems. May be important with long-term monitoring when evaluating mass balance issues.
Rain Gauge	Location of the rain gauge that will be used for evaluating flow monitoring results. Useful to note the location of secondary rain gauge for rainfall comparisons and as a backup if the primary gauge data is unavailable.

Land Use. Suggested land use types to use when describing the tributary watershed area are provided below. These land use types provide enough information for hydrologic computations by the NRCS Curve Number (CN) method as well as the Rational Method. The pervious area descriptions are useful when estimating depression storage and overall roughness coefficients when computing runoff with SWMM. Additionally, these categories are commonly used for characterizing average pollutant loads. When categorizing by land use, quantify the area of each type and express either as an area or as a percent of the total watershed.

Commercial-Business

- Downtown CBD
- Office
- Retail
- Automotive Services
- Restaurants

Industrial

- Light
- Heavy

Residential

- Apartments
- 1/8-acre lot (town houses) (est. 65% impervious)
- 1/4-acre lot (est. 38% impervious)
- 1/3-acre lot (est. 30% impervious)
- 1/2-acre lot (est. 25% impervious)
- 1-acre lot (est. 20% impervious)
- 2-acre lot (est. 12% impervious)

Streets, Roads and Parking Lots

- Paved; curbs and storm sewers (excl. ROW)
- Paved; open ditches (incl. ROW)
- Gravel (incl. ROW)
- Dirt (incl. ROW)
- Median Area, turf

Railroad Yard

Urban Open Spaces (lawns, parks, golf, cemeteries)

- Poor (grass cover <50%)
- Fair (grass cover 50% to 75%)
- Good (grass cover >75%)

Natural

- Meadows
- Woodland & Forest

Agricultural

- Pasture and Rangeland
- Orchard
- Vegetable Farming

Unknown or Other

Impervious Land Cover. Impervious land covers for the City of Grand Rapids were delineated in GIS based on 6-inch spatial resolution orthoimagery flown in 2014. The dataset is useful to quantify the total impervious area within the watershed and estimate the directly connected impervious area. These variables are important when calculating hydrology with SWMM. The feature types mapped are listed in Table 3. Land cover changes over time, therefore the GIS data should be checked and edited as needed before using the information.

Table 3 Impervious Cover Types

	Paved	Unpaved
Roads and Highways	Asphalt, concrete and brick roads	Gravel and compacted dirt roads
Alleys	Asphalt, concrete and brick alleys	Gravel and compacted dirt alleys
Parking Lots	Asphalt, concrete and brick parking lots	Gravel and compacted dirt parking lots
Driveways	Asphalt, concrete and brick driveways	Gravel and compacted dirt driveways
Sidewalks	Asphalt, concrete and brick pedestrian and bicycle pathways. This class includes sidewalks along roadways, golf course paths, park walkways, bicycle and walking trails, and cemetery walkways.	Gravel and compacted dirt pedestrian and bicycle pathways. This class includes sidewalks along roadways, golf course paths, park walkways, bicycle and walking trails, and cemetery walkways.
Railroads	NOT USED. Where RR tracks cross paved roads, highways, alleys, parking lots, driveways, sidewalks and other paved surfaces these feature classes are used instead of RR.	Railroad tracks on aggregate base.
Other	Asphalt, concrete and brick paved surfaces not included in other feature types. Examples include airport runways and taxiways, tennis courts, shelters, and building remnants (collapsed buildings where there are still remnants of at least 1 wall). Material storage on top of this surface should be included in this feature type; e.g. if a pile of gravel or mulch is on a paved surface, don't delineate it separately.	Gravel and compacted dirt surfaces not included in other feature types which show evidence of heavy vehicle use. Includes surfaces with some vegetation but strong evidence of heavy vehicular traffic over the surface (i.e., wheel tracks). Examples include material storage yards typical around industrial operations and some commercial businesses. Storage yards includes neat and tidy material storage as found at landscape companies using concrete barriers to contain materials, and unorganized yards where materials appear scattered in random piles. Also includes mining operations such as a gravel pit.
Patios/decks	Wooden decks, concrete patios, and other deck construction	
Buildings	Building roofs	

3.0 HYDROLOGIC IMPACT

This section begins by defining terminology surrounding the system models and then discusses various types of analysis' used when looking at the big picture issues and commonly asked questions associated with the performance of a GI practice.

3.1 HYDROLOGIC SYSTEM MODEL

A hydrologic system model approximates the actual system; its inputs and outputs are measurable hydrologic variables and its structure is a set of equations linking the inputs and outputs. The objective of a hydrologic analysis is to predict the output. Often the variables are measured under one set of environmental conditions (e.g. a discrete rainfall event) and then the model is used to predict the output under a different set of conditions (e.g. the average annual). The focus of the system, in this case, is a GI practice. The GI practice accepts inflow, transforms it and has outflow.

3.1.1 Inflow

The primary sources of ***inflow*** are:

- ***Inlet flow*** through one or more defined inlet such as a curb cut. Use direct flow measurements whenever possible. Inlet flow monitoring is discussed in Section 4.1.1 (page 17).
- ***Overland flow*** enters the GI practice as sheet flow or shallow concentrated flow from the surrounding area site grading. Overland flow is difficult to monitor directly and instead is typically estimated with standard hydrologic methods.
- ***Direct rainfall*** falling on the GI practice area. Quantify the direct rainfall from a nearby rain gauge. Use the total rainfall quantity, i.e., do not subtract initial abstractions. Refer to Section 5.1 on page 34.

Other examples of inflow are listed below. These sources are typically ignored unless there is a known source, or a water balance of the data shows the addition of water.

- Leaky watermains or exfiltration from other nearby utilities.
- Irrigation systems.
- High groundwater levels.

Inflow to a GI practice may then be expressed as:

$$Inflow = Inlet\ Flow + Overland\ Flow + Direct\ Rainfall$$

In some cases, not all the runoff generated from the drainage area upstream of a GI practice enters the practice. Some water may ***bypass*** the inlet. Bypassed flow may be unintended from poor design or construction or may be purposeful.

3.1.2 Outflow

Flow may leave a GI practice through a variety of methods, which we'll refer to as ***outflow***. The different ways outflow may occur includes:

- Discharge through a ***subsurface drain*** (*underdrain*). Underdrain flow should be monitored directly. Depending on the site, discharge monitoring of the underdrain may be included with the outlet discharge monitoring. Refer to Section 4.10 (page 32) for additional information.
- Discharge through a controlled ***outlet***, such as a beehive catch basin in the GI practice or other defined structure often including orifices, weirs, or pipes. Quantify with direct flow measurements. May be combined with flow from the underdrain depending on the site. Refer to Section 4.13 (page 33) for additional information.
- Water spilling over the sides of the GI practice or other uncontrolled releases of water during large storm events is considered ***overflow***. This also includes sheet flow off pervious pavement surfaces. Refer to Section 4.14 (page 33) for additional information.

Outflow from a GI practice may then be expressed as:

$$Outflow = Subsurface\ Drainage + Outlet\ Flow + Overflow$$

3.1.3 Infiltration and ET

Water may also leave a GI practice by soaking into the subgrade and through evapotranspiration (ET). This is often the intention or purpose of the GI practice.

- ***Infiltration*** into the subgrade soil. The term *infiltration* is typically associated with the vertical movement of water into the soil. Horizontal movement of water into the surrounding soil is often ignored but may be important to consider in some situations. Sometimes the term *exfiltration* is used to describe water in the GI practice seeping into the surrounding soil, regardless of direction. *Subsurface flow* is another general term used to describe the movement of water through soil. Additional information on checking the subgrade infiltration is provided in Section 4.11 (page 32).
- Water follows the path of least resistance. Some water is typically lost to horizontal movement away from the GI practice. Horizontal water lost is often ignored or assumed to be included with the infiltration. If the infiltration rates are determined from flood tests, then the horizontal movement is already included.
- ***Evapotranspiration*** (ET) is the process by which water is transferred from the land to the atmosphere by evaporation from the soil (and other surfaces) and by transpiration from vegetation. ET typically represents a very small quantity of water relative to the duration of a single rain event and is often ignored. ET should be included for long term water budgets, e.g., average annual quantification. ET is either estimated mathematically or quantified directly from lysimeter measurements. Refer to Section 4.4.7 (page 28) for additional information.
- Another way in which water leaves a GI practice is through the sand backfill used around underground utilities. Water flows easily through sand backfill. An example of this is an underdrain pipe connecting to a nearby manhole outside of the GI practice and other underground pipes leading away from the manhole. Water flowing through the utility trenches may become a source of infiltration or inflow (I/I) into a sewer pipe or leak into basements. Anti-seep collars or trench dams are used to prevent unintended subsurface flow through utility trenches.

The term ***retention*** is used to describe water that is permanently removed from the manmade drainage system through infiltration and ET. Retention may be expressed as:

$$Retention = Infiltration + Evapotranspiration$$

Retention systems may include permanent pools of water or other long-term storage of water such as a traditional retention basin. Hence the storage component may need to be considered in the retention equation depending on the time duration selected. Regardless, the only way a retention pool of water is drawn down is through infiltration and ET.

In many of the basic hydrologic data analyses, the infiltration and evapotranspiration (ET) are either not needed or are assumed to be the result. For example, when determining the net volumetric change in runoff due to the presence of the GI practice, the net change is determined by the difference of the inflow and the direct discharge. For this calculation, independently measuring the infiltration and ET is not needed. In fact, the assumption is that the water that is not directly discharged is lost to infiltration or ET.

3.1.4 Storage

Water stored in the system, either at the start or end of an event, may be stored in the surface storage (Section 4.3), held in the pore space of the engineered soil (Section 4.4), held in the pore space of an aggregate (Section 4.7), in the porous pavement (Section 4.6), or some type of subsurface storage vault (Section 4.8). The amount of water in the system at the beginning and end is quantified with direct measurements. Quantify with direct measurements for soil moisture or with depth measurements in aggregate layers or open storage systems.

3.2 DATA ANALYSIS

The data analysis begins with a careful review of the monitoring data and quantification of the variables not directly monitored. In a comprehensive study, it is recommended to organize the data as time-series data (i.e., hydrographs). This allows for direct comparison of each unit operation with time. A spreadsheet is the ideal tool for this analysis. The time series information should be extended for several days as the system drains. If another rainfall event occurs before the first event has completely drained, then either include the additional rainfall in the analysis or the continued drawdown of the first event will need to be estimated. Each discrete event monitored should be analyzed independently.

When reporting results for discrete monitored events, it's useful to report relative to the amount of rainfall. That is to say that we expect the GI practices to perform very well on small rainfall events and gradually reduce in performance as the rainfall increases.

When average annual estimates or extrapolation to discrete design events are desired then a hydrologic computer model is used. The model is first calibrated to the collected data and then used in a predictive fashion for the desired results. When computing average annual information, it is recommended to use at least 10 years of continuous rainfall information.

3.2.1 Mass Balance

Does my data make sense?

When analyzing a GI practice, it's often useful to consider a mass balance of the water. The analysis often relies on monitoring data for some information and basic hydrologic calculations methods for other information. The idea is to look for a reasonably good fit of information. When there are unexplained significant increases or losses of water then some of the less common sources should be investigated as discussed in Section 3.1 (e.g. high groundwater, leaky pipes, subsurface flow through utility trenches etc.).

$$Inflow + Storage_{Start} = Outflow + Retention + Storage_{End}$$

In the case of a water harvesting system an additional term is needed to describe the reuse of the water. In a water harvesting system, the water is reused when it's not raining and therefore typically requires a long-term analysis.

3.2.2 Net Volume Reduction

What is the net volume reduction achieved by the green infrastructure project?

The net runoff volume reduction due to the presence of the GI practice is calculated from the difference of the inflow and the outflow. The inflow and outflow are expressed as a volume, which means that a start and stop time must be established. When designing a GI practice, a duration is typically selected for complete dewatering (typically 1 to 3 days). The design duration is typically assumed for the stop time. The reduction may be expressed as a percentage by dividing the difference by the inflow.

$$Net\ Volume\ Reduction = Inflow\ Volume - Outflow\ Volume$$

$$Net\ Volume\ Reduction\ (\%) = \frac{Inflow\ Volume - Outflow\ Volume}{Inflow\ Volume}$$

The change in the net volume is the same as the *volume retained*. Retention is the permanent removal of the water from direct discharge, whereas detention is the temporary capture and controlled release of the water.

$$Net\ Reduction = Retention$$

$$Inflow - Outflow = Infiltration + ET$$

The above equations assume that the GI practice is completely dewatered. When the practice is not completely dewatered the change in stored water must be included.

With continuous flow monitoring data, the net volume reduction can be determined for each rainfall event. Results are then suggested to be plotting as a function of total rainfall amount, and a regression curve can be fit to the data. Results can then be extrapolated to designated discrete design storms.

A simple way to estimate retention is the storage volume of water below the underdrain or lowest outlet elevation. This can be thought of as a static retention volume for a practice. Since infiltration occurs over time, when the inflow and outflow are considered to occur over time, the observed retention can be greater than the computed static retention. Accounting for changes over time are best determined based on the flow monitoring data but may also be calculated in a spreadsheet or computer software program such as SWMM.

Average annual retention or volume reduction may be determined by applying monitoring results, as a function of the total rainfall, to tabulated rainfall event data. Rainfall events are assumed to be independent of one another and annual values are based on the sum of the retention for individual events within the year. Values can also be estimated using a computer software program such as SWMM or the National Stormwater Calculator.

3.2.3 Volume Managed

Sometimes quantifying the total volume managed by a GI practice is important. The volume managed is an expression of how much water entered the GI practice and was controlled in some fashion. Most GI practices are designed to handle the small frequent storm events. During large storm events flow may be bypassed around the inlet or the practice overflows. It's important to not include bypassed flow in the inflow measurement.

$$Volume\ Managed = Inflow\ Volume - Overflow\ Volume$$

With continuous flow monitoring data, the volume managed can be determined for each rainfall event. Results are then suggested to be plotting as a function of total rainfall amount, and a regression curve fit to the data. Results can then be extrapolated to designated discrete design storms or on an average annual basis as discussed in Section 3.2.2.

3.2.4 Peak Flow Change

What is the reduction in the peak flow rate due to the green infrastructure project?

The change in peak flow due to the presence of the GI practice is calculated as the difference of the inflow peak rate and the outflow peak rate. It's important to consider the complete time-series data when looking at peak rates since the peak rate of component may occur at a different time. Peak flow change may be expressed as a percentage by dividing the difference by the inflow peak flow rate. Peak flows are a function of the rainfall and should be computed for each rainfall event independently.

$$Net\ Peak\ Flow\ Change\ (\%) = \frac{Peak\ Inflow\ Rate - Peak\ Outflow\ Rate}{Peak\ Inflow\ Rate}$$

3.2.5 Change in Time-to-Peak

What is the increased time of concentration resulting from the green infrastructure project?

The change in time-to-peak is computed as the difference in time from when the inflow rate peak occurred, and the outflow peak rate occurred. It's important to consider the complete time-series data when looking at peak rates since the peak rate of component may occur at a different time.

$$Change\ in\ Time\ to\ Peak = Time_{Peak\ Inflow} - Time_{Peak\ Outflow}$$

3.2.6 Drain Time

The time it takes to completely dewater a GI practice can be determined based on the inflow and direct discharge monitoring data if the outlet completely dewaters the practice. If the GI practice has an internal water storage zone, then metering the water depth or soil moisture can be used to calculate the drain time. Drain time is important because the goal is to maximize the duration for infiltration but also drain the system so it's ready for the next storm event.

Figure 2 Flood Test to Monitor Performance Including the Drain Time

3.2.7 CN and Volumetric Runoff Coefficients

Another useful exercise is to calculate the NRCS Curve Number (CN) and volumetric runoff coefficient (C) for the watershed. Often textbook values are used for these coefficients, however local site-specific information is always preferred. The CN and C's are calculated based on the measured rainfall and the inlet flow measurements.

It may be tempting to calculate the CN and C based on the direct discharge. This is sometimes interpreted as the CN or C from a GI practice. For example, what is the CN of porous pavement. It is strongly recommended to <u>not</u> calculate CN's and volumetric runoff coefficients based on the direct discharge. The reason for this is that every GI practice is unique in its size, shape and discharge characteristics along with unique subcatchment characteristic of the tributary drainage area. A CN or C calculated for one GI practice cannot be used at a different GI practice.

4.0 ASSESSMENTS BY COMPONENT

This section looks at rapid assessment techniques that can be used to evaluate individual components of a stormwater practice. These assessments may be used to record baseline conditions (e.g., infiltration rate of subgrade during construction or surface infiltration immediately after construction) and may be repeated over time to document changing conditions (e.g., how does the surface infiltration change over time). The assessments may also be used to determine when maintenance is needed (e.g., when is vacuuming of a porous pavement surface required). Equipment used is either stand-alone test equipment (e.g., an infiltrometer) or continuous monitoring equipment installed on a short-term temporary basis. Some assessment techniques require a sample collection and analysis in a laboratory. The rapid assessment approaches may be used to troubleshoot an underperforming stormwater practice.

Table 4 provides an overall summary of the various assessment methods, and when the assessment is recommended, for each component. The information in this section is loosely organized to follow water as it enters, flows through, and exits a stormwater practice.

Table 4 Assessments by Component

Component	Phase			Method		Asset Mgmt Condition	Objective
	Design	Construction	Post- Construction	Continuous Monitor	Rapid Assessment		
Inlet Structure(s)						✓	
Inflow Monitoring			✓	✓			Hydrologic impact studies.
Inlet Efficiency			✓		✓		Check performance to inform future designs.
Pretreatment			✓		✓	✓	Quantify effectiveness. Extrapolate discrete measurements to average annual for reporting.
Surface Features						✓	
Storage Zone		✓			✓		Confirm proper construction. Significant impact to performance estimations.
Preferential Flow Paths			✓	✓	✓		Troubleshoot irrigation and short circuiting.
Overall, Flood Test			✓	✓	✓		Overall performance check of infiltration, inlet/outlet controls, and quantification of retention and detention volumes.
Soil Filter Media						✓	
Soil Mix		✓			✓		Document specific assets. Evaluate performance with other tests.
Infiltration		✓	✓	✓	✓		Track long term performance and evaluate when soil media needs to be replaced.
Compaction		✓	✓		✓		Confirm proper construction. Impacts infiltration and vegetation health.
Bulk Density		✓	✓		✓		Confirm proper construction. Impacts infiltration and vegetation health.
Effective Porosity		✓			✓		Document actual values for material installed. Used in performance calculations and to inform future designs.
Soil Moisture		✓	✓	✓	✓		Required for some infiltration and compaction tests. May be used for long term hydrologic impact studies to look at storage and ET.

Component	Phase			Method		Asset Mgmt Condition	Objective
	Design	Construction	Post- Construction	Continuous Monitor	Rapid Assessment		
Evapotranspiration			✓	✓	✓		Long term hydrologic impact studies; often a secondary issue.
Vegetation		✓	✓		✓	✓	Check performance to inform future designs.
Pavement						✓	
Infiltration		✓	✓		✓		Track long term performance evaluate when cleaning is required.
Aggregate Storage Layer		✓			✓		Document actual values for material installed. Used in performance calculations and to inform future designs.
Subsurface Storage Vaults		✓			✓		Confirm proper construction. Significant impact to performance estimations.
Cleanouts/Observation Ports		✓				✓	Access ports to investigate subsurface components.
Subsurface Drains						✓	
Outflow Monitoring			✓	✓			Hydrologic impact studies
Subgrade Infiltration	✓	✓	✓	✓	✓		Significant impact to performance estimations. Track long term performance evaluate when cleaning is required.
Observation Wells		✓				✓	Access ports to investigate subsurface components.
Outlet Structure(s)						✓	
Outflow Monitoring			✓	✓			Hydrologic impact studies.
Outlet Efficiency			✓		✓		Check performance to inform future designs.
Overflow						✓	
Outflow Monitoring			✓	✓			Hydrologic impact studies.

4.1 INLET

Inlets concentrate and route flow into a stormwater practice. For bioretention systems, inlets are typically either a curb cut or a catch basin with a pipe leading to the bioretention. These types of inlets are located along curbed roadways or parking areas and are characterized by gutter flow along the curb of the pavement. Water may also enter a green infrastructure practice as sheet flow, as is commonly the case with porous pavement systems and bioretention systems in areas without curb and gutter (e.g., a bioswale along a roadway).

4.1.1 Inlet Flow Monitoring

How much water is entering the practice?

Monitoring the water passing through an inlet is accomplished by selecting appropriate primary and secondary flow measurement equipment. Inlet monitoring is typically accomplished either with a weir and pressure transducer set up or when the flow is channelized in a pipe a depth-velocity sensor can work well. Considerations should be given for sediment and debris in the flow stream, vandalism, access to the equipment and a power supply.

For long term monitoring applications, consider adding dedicated structures during design and construction. For example, include a flow through manhole between the inlet from the street or paved surfaces and the point of discharge into the bioretention practice. The dedicated structure can be sized to house the preferred monitoring equipment, e.g., a weir or flume. A dedicated structure also protects against vandalism, houses the data logging equipment along with the primary and secondary flow measuring devices, and provides consistent high-quality monitoring results.

Inflow from sheet flow sources are much harder to monitor. Typically, the flow stream is concentrated either upstream of the sheet flow with a level spreader or downstream of the sheet flow into a channel. In the case of the upstream case with a level spreader, the level spreader acts as a weir so monitoring is accomplished with a pressure transducer upstream of the weir. An example for this might be when quantifying the flow entering a filter strip. Another option is to consider a rapid assessment technique relying on visual observations of the spatial distribution and depth of flow over the sheet flow area. Observations may be enhanced by dying the source water. An application of this might be when evaluating the effectiveness of the sheet flow condition across a filter strip. Often when flow is entering a green infrastructure practice via sheet flow, such as the run-on onto a porous pavement system, the inflow is estimated mathematically rather than a direct measurement.

Figure 3 Inlet Flow Monitoring

4.1.2 Inlet Efficiency

Is the inlet capturing the intended water or is the water bypassing the system?

The inlet efficiency is the fraction of flow entering the inlet divided by the total flow. Inlet efficiency is affected by many variables such as the transverse slope of the pavement (or gutter pan), the longitudinal slope of the pavement (affects the velocity of the water), the type of opening (grate or open) and the width of the opening. General design equations for sizing a curb opening and catch basins are available from FHWA.

Determining how well an inlet is operating in the field may be assessed by simulating rainfall conditions. A basic approach to determining the inlet efficiency and maximum flow rate entering the inlet is to discharge a range of flows along the gutter, develop a spread-discharge rating curve upstream of the inlet and measure the spread downstream of the inlet. The inlet flow is then calculated as the difference between the flow upstream of the inlet and the flow that doesn't make it into the inlet. The source of the water is typically best provided from a nearby fire hydrant, although a water truck can be used.

Equipment

- Hydrant water meter (to measure flow rate) and wrench to open the hydrant
- Length of fire hose and sandbags to hold the hose securely
- Tape measure to measure the flow spread
- Carpenter level and ruler to measure the cross-sectional geometry of the gutter (optional)
- Survey level and tape to measure the longitudinal slope of the gutter (optional)

Approach

Figure 4 Inlet Efficiency Determination

1. Based on the watershed characteristics, estimate the peak flow expected upstream of the inlet. This is most easily done using the Rational Method equation knowing the drainage area, looking up a Rational coefficient (C), and determining the rainfall intensity based on time of concentration and desired design storm. Using a 10-year design storm for the rainfall is suggested. The peak flow rate expected establishes the upper limit to the desired range of simulated flows. It is suggested to calculate the expected peak flow from a range of design storm recurrence intervals for later use in comparing to the inlet efficiency (Step 8).
2. Locate a nearby fire hydrant upstream of the inlet to be assessed. Water needs to be discharged into the gutter a sufficient distance upstream of the inlet to allow uniform flow conditions to establish. A distance of at least 50 feet is suggested. Sandbags and bricks can be used to help guide flow from the firehose.
3. Connect the meter to the fire hydrant and the fire hose to the meter. Layout the firehose to direct water into the gutter pan. Use sandbags to prevent the end of the firehose from moving.
4. Open the hydrant to initially let out a relatively low flow rate. Record the flow rate from the hydrant meter. Measure the average spread of water in the gutter upstream and downstream of the inlet. The measurements should be taken a sufficient distance from the inlet to avoid the influence of the inlet on the spread distance.
5. Repeat the spread measurements at a range of flow rates up to the maximum flow rate calculated in Step 1 or the maximum discharge available from the hydrant, whichever is smaller. Be sure to allow enough time at each flow rate for the gutter flow conditions to reach an equilibrium.
6. Graph the spread-discharge relationship using the spread measurements upstream of the inlet and the metered hydrant flow rate. Best fit a curve to the data points. This establishes the spread-discharge relationship for the site.
7. Calculate the discharge rate downstream of the inlet based on the measured spread and the spread-discharge relationship (Step 6).
8. Calculate the inlet flow rate by subtracting the gutter flow from upstream of the inlet from the gutter flow downstream of the inlet. The inlet efficiency at each flow rate may be calculated as the inlet flow divided by the gutter flow upstream of the inlet. The inlet efficiency can be reported for a range of design storms if the peak flows were calculated in Step 1.
9. Compare the measured results with the intended design.

Optional

10. Survey the longitudinal slope of the pavement and gutter pan. Ideally, the longitudinal slope should be uniform and constant upstream and downstream of the inlet. Also measure the cross-sectional geometry of the pavement and gutter pan. Calculate the theoretical gutter flow rates based on FHWA equations and compare to the measured values. Adjust calculation coefficients to best fit the data and keep track of for future design considerations.
11. Fit the inlet to directly measure the inflow. This typically involves the use of a weir as a primary device and pressure transducer to record depth. Direct inlet flow measurement may be needed in cases where the gutter flow rate downstream of the inlet cannot be measured or when additional accuracy is desired.

Notes

12. During testing, pay attention to the water surface level in the bioretention practice. High water surface levels in the bioretention may impact the hydraulics of the inlet. The system may need time to dewater in between flow tests. In extreme situations, the bioretention may be pumped out during the flow tests to prevent impacting the inlet hydraulics.

The length of a curb-opening inlet required for total interception of gutter flow on a pavement section with a straight cross slope is expressed by:

$$L_T = K_u Q^{0.42} (S_L)^{0.3} \left(\frac{1}{nS_X}\right)^{0.6}$$

where L_T = curb-opening length required to intercept 100% of the gutter flow, ft
K_u = 0.6 English units (0.817 for SI units)
Q = peak flow, ft3/s
n = Manning roughness coefficient
S_L = longitudinal slope of the gutter, ft./ft.
S_X = cross slope of the gutter, ft./ft.

The idea is to conduct tests on an inlet comparing the peak flow intercepted against the curb-opening length. The test results should be compared against the FHWA curb-opening equation. When differences are noted, adjustments to the equation should be documented for future design use. The results can also be incorporated into hydrologic models predicting the overall performance of the GI practice.

4.2 PRETREATMENT

Pretreatment typically focuses on sediment removal but may also apply to trash and debris in some cases. A common pretreatment approach is a sump (for small systems like a bioretention garden) and a sediment forebay (for large systems like detention basins). Manufactured treatment devices (MTD) are also becoming popular to remove sediment and trash.

How frequently do you need to clean the pretreatment device?

Is sediment resuspending during high flows?

The basic approach to assessing the pretreatment device performance is to frequently visit and record the accumulation of sediment, trash and debris over time. By knowing the geometry of the pretreatment device, the volume of sediment accumulation can be determined from a simple depth measurement. It is often difficult to determine the amount of sediment and trash that is bypassing. Note that this rapid assessment method requires frequent site visits over a long period of time (usually at least a year).

Equipment

- Vacuum truck, or equivalent cleaning equipment
- Manhole hook or other device to remove manhole and catch basin lids (if needed)
- Grade rod or measuring tape for depth measurements
- High powered flashlight
- Data collector or other method to record results

Approach

1. Obtain the geometry of the pretreatment system from construction drawings, manufacturer information or hand measurements. Develop a depth-volume relationship to know the volume of sediment based on a depth measurement.
2. Clean the pretreatment device before beginning (optional).
3. Note the sediment depth at which maintenance is recommended based on the design intent. Consult the manufacturer for the recommended depth of proprietary devices. The rule of thumb for standard sumps is to clean when the sump is half full.

4. Measure and record the depth from the rim of the manhole or catch basin casting down to the invert or bottom of the pretreatment device. This is the baseline measurement.
5. Periodically visit the site and measure the rim down to the top of the accumulated surface of sediment. Note: If the surface varies, take several dropdown measurements and calculate the average. Record the dropdown measurement along with the estimated sediment volume based on the depth-volume relationship from Step 1.
6. When floatable trash and debris are of interest, the same basic method applies. A simple measurement technique is needed to determine the volume. For example, this could be a dropdown measurement to the top of the floatable debris and a second measurement to the water surface level; the volume is then the difference. In the case where the floatable trash and debris does not completely cover the water surface, an estimate of the percent coverage may be used.
7. Observe the stormwater system immediately downstream of the pretreatment device. Look for signs of sediment, trash and debris. Record observations.
8. Note the rate of accumulation over time. Plotting the data is recommended. As the rate of accumulation slows down over time indicates that the system is no longer permanently storing the sediment and needs to be cleaned. Also consider if or when sediment, trash and debris were observed downstream of the pretreatment device.

Optional

9. Conduct site visits immediately before and after big storm events. This will help address the question if the sediment is resuspending and if floatable trash is escaping during high flow conditions.
10. Theoretically, higher flows can be simulated from a fire hydrant or other water source to evaluate if sediment is being resuspended. This may not be practical to do in the field. Other approaches involve physical hydraulic laboratory simulations and computational fluid dynamic modeling.
11. Collecting a sediment sample and analyzing the particle size distribution will help determine what particle sizes are efficiently trapped by the pretreatment device.

4.3 SURFACE STORAGE ZONE

4.3.1 Constructed as Designed

Was the stormwater practice constructed at the right elevations and with the intended storage volume?

Proper construction of a stormwater storage system is critical. Constructing the system at the right elevations and with the intended area-volume relationship is key to successful stormwater management.

One research study in North Carolina assessed the accuracy of bioretention installations (Wardynski, B. J. and W. F. Hunt, 2011). This study surveyed bioretention practices after construction and compared the survey results to the design drawings. Only 17 percent of the bioretention practices were found to be adequately constructed relative to the design.

Table 5 Case Study Constructed Storage Relative to Design

Category	Percent of Design Volume	Percent of Bioretention Practices in this Category
Severely Undersized	<-25%	28%
Moderately Undersized	-25% to -10%	22%
Adequate	-10% to 10%	17%
Moderately Oversized	10% to 25%	17%
Severely Oversized	>25%	17%

A simple rapid assessment technique to evaluate if a stormwater practice was constructed at the right elevation and with the right surface area-volume relationship is to survey the system after construction. The survey can be used as an independent check of construction and to establish a baseline condition. Consider requiring an independent survey the responsibility of the contractors during construction. Additional surveys years after construction (e.g., 5, 10, 20 years later) may be used to show how the system changed over time.

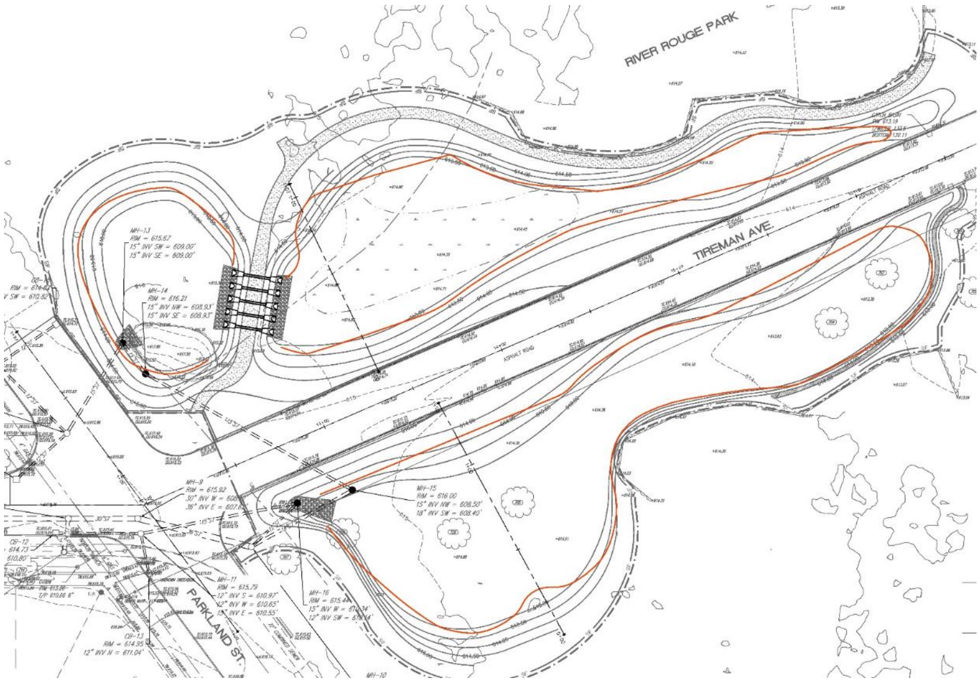


Figure 5 Designed vs Constructed Storage Zone

4.3.2 Preferential Flow Paths

Is the water entering the stormwater practice spreading out across the entire surface area or is it following preferential flow paths?

Water in very large bioretention areas may not evenly extend across the surface area. Water tends to naturally form in shallow concentrated flow streams after relatively short sheet flow conditions. Some plants in the bioretention may not receive as much water as others resulting in vegetation die off. Planting plans should account for the anticipated differences in available water. As a design consideration, it may be beneficial to place aggregate along preferential flow paths.

Figure 6 Preferential Flow Path Monitoring

To evaluate if preferential flow paths are occurring in a bioretention system, a visual assessment can be conducted of the water spread as water is introduced into the bioretention practice. Another approach is to survey the surface of the storage zone. A traditional survey of the surface may lack the detail needed to quantify preferential flow paths based on the subtle elevation changes and interference vegetation and mulch may provide. Even so, the starting point is a survey of the practice. Several factors are recommended to enhance the visual assessment including:

- using potable water from a nearby fire hydrant instead of relying on rainfall
- introducing a tracer dye into the water to enhance the visibility (EGLE permit required to use tracer dyes)
- laying out a grid of stakes across the surface as reference points for measurements
- videotaping the study with both stationary and mobile cameras

4.3.3 Overall Function – Flood Test

Does it work?

I just want to know if overall the bioretention system is functioning

Sometimes we just want to know if the overall system is functioning. A rapid assessment approach to see if the whole stormwater practice (like a bioretention) is functioning is to flood it with water and observe what happens. Using potable water from a nearby hydrant provides a reliable way to know how much water is in the bioretention to start.

Manual flood tests can be conducted to:

- Provide an independent check on inlet and outlet flow monitoring equipment.
- Conduct net volume reduction tests
- Conduct volume managed tests.
- Conduct an inlet efficiency test.
- Check for preferential flow paths.
- Check for overflow points.
- Determine the drawdown duration.
- Develop an overall stage-discharge relationship for the entire GI practice.
- Determine the rate of infiltration of the subgrade (temporarily close outlets if needed).
- Determine the outlet discharge rate at different heads.
- Determine the water volume holding capacity (monitor with hydrant meter or inlet flow monitor)
- Check the functionality of the underdrains.
- Provide an education opportunity for the public and municipal staff.

Figure 7 Bioretention Flood Test

Equipment

- Hydrant water meter and wrench to open the hydrant
- Length of fire hose and sandbags to hold the hose securely
- Additional sandbags to direct water into bioretention, if needed
- Grade rod to measure water depth (optional)
- An electronic stage recorder may be used to measure drawdown (optional)
- Video camera or time lapse camera (optional)

Approach

1. Direct flow to the bioretention practice from a fire hydrant. Stop filling the practice when the water depth reaches the maximum level before overflowing or when the system reaches an equilibrium state (i.e., when the depth of water is no longer increasing). Record at what time flow from the fire hydrant was started and stopped.
2. Periodically check the water level over the intended drawdown period. Most bioretentions are intended to be dewatered within 1 to 3 days.

Optional

3. Record the total volume of water used to fill the bioretention practice and the rate at which the water was delivered. Compare these values to the design.

4. Mount a grade rod or staff gauge in the deepest part of the bioretention and record depth observations over time. Note this can be further enhanced by using a video or time lapse camera pointed at the grade rod.
5. Measure the outlet flow rate as a function of the water head in the bioretention.

Notes

6. If a valve is included on the underdrain it is suggested to start the test with the valve in the closed position to aid in filling the bioretention with water. Having the valve closed will also typically produce the most limiting hydraulic condition, i.e., the longest drain time.
7. A flood test may also be used to calibrate the outlet flow condition to the desired setting.

4.4 SOIL FILTER MEDIA (BIORETENTION)

The soil media of a bioretention practice plays a key role in filtering the stormwater runoff, temporarily storing runoff water, and growing the vegetation. There are a host of variables that can be and should be considered. Two important variables for managing the quantity of stormwater runoff are the rate at which water flows through the soil media and the ability to grow vegetation. The rate at which water flows through the soil media is the hydraulic conductivity, which is commonly determined by measuring the infiltration rate. Decreasing infiltration rates from year to year indicate the system is clogging and may reduce the volume of water treated. The ability to grow vegetation is commonly evaluated based on visual observations of the vegetation (refer to Section 4.5). Other variables to consider include: soil type or composition; soil compaction; the temporary water storage volume (related to porosity and field capacity); and the rate of evapotranspiration. Each of these topics is discussed below.

4.4.1 Soil Mix

The soil mix for a bioretention is specified as part of the design. Testing of the mix components should be performed before and during construction. Testing should include: relative fraction of organic and inorganic materials, particle size distribution of the inorganic material, completeness of composting of organic amendments, and pH. These tests may be used after construction, although the rate of infiltration and vegetation observations are typically more important.

Nutrient soil testing is also an option which looks at which nutrients are present and which ones need to be added depending on the plant(s) you are trying to grow. Nutrient soil testing is available from Michigan State University (MSU) Soil and Plant Nutrient Laboratory (SPNL) (http://www.spnl.msu.edu/) from county extension operations.

4.4.2 Infiltration

What is the infiltration rate through the soil media?

The infiltration rate of the engineered soil media is not as important as the rate of infiltration through the subgrade. Nevertheless, it is an important variable to understand. The ratio of the drainage area to the surface are of the soil coupled with the rainfall intensity determines the rate at which water will need to infiltrate in order to not be a limiting factor in the design. For example, if the ratio of the drainage area to the bioretention surface area is 10:1 and the rainfall intensity is 2 inches per hour, then the equivalent rate to the bioretention surface is 20 inches per hour. Typical bioretention soil is on the order of 6 to 10 inches per hour allowable infiltration rate. If water is coming in at 20 inches per hour but can only infiltrate at 8 inches per hour, then ponding will occur. Actual inflow rates need to account for the various contributing land cover types and are attenuated by the travel time. The point is that knowing the engineered soil infiltration rate is important for design and can be customized to the different soil mixes. Tracking the infiltration rate over time will provide information on when maintenance is needed to refresh the soil due to clogging.

Various methodologies and devices are available to measure infiltration rates. Methods typically use either a constant or falling head of water above the surface being measured.

The most accurate method to determine if a bioretention practice is functioning correctly is a simple flood test. This simple test involves flooding the entire bioretention (or other infiltrating BMP) with water and recording the time for complete drawdown to occur (i.e., no standing water on the surface). The practice may be flooded with water from a fire hydrant or other source, or a natural rainfall event. An electronic stage recorder may be used to measure drawdown. Alternatively, a staff gage and wildlife camera may also be used to record the drawdown. The rate of drawdown is calculated by dividing the initial water depth by the drawdown time. Media drawdown rates should fall between 1 inch per hour and 8 inches per hour.

Figure 8 Bioretention Flood Test

Table 6 provides a summary of infiltration test methods for soil.

Table 6 Soil Infiltration Tests

Name	Method
Flood Test	Described in text
Percolation Test	Refer to Low Impact Development Manual for Michigan, Appendix E (2008)
Double-ring infiltrometer	Refer to Low Impact Development Manual for Michigan, Appendix E (2008)
Double-ring infiltrometer	ASTM D3385
Modified Philip-Dunne	ASTM D8152

4.4.2.1 Soil Infiltration Tests

There are a variety of test methods. The double-ring infiltrometer testing apparatus consists of two concentric metal rings that are driven into the ground and filled with water. A double-ring infiltrometer test estimates the vertical movement of water through the bottom of the test area. The outer ring helps to reduce the lateral movement of water in the soil from the inner ring. Research has shown that the use of a second ring often does not increase the accuracy of the test, however accuracy has been shown to improve with increasing ring diameter (Reynolds, Elrick, Youngs, & Amoozegar, 2002). A percolation test allows water movement through both the bottom and sides of the test area. For this reason, the measured rate of water level drop in a percolation test must be adjusted to represent

Figure 9 Bioretention Soil Media Infiltration Test

the discharge that is occurring on both the bottom and sides of the test hole. Alternatively, a permeameter can be used to field test infiltration rate. The Modified Philip-Dunne permeameter is easy and commonly used.

When conducting soil infiltration tests, a minimum of one (1) test is recommended on GI practices located on single family residential lots and three (3) tests are recommended on other land use lots and within the rights-of-way. One (1) additional test should be added for each additional 5,000 square feet of GI practice surface area. When using a Modified Philip-Dunne test method the minimum number of tests is five (5) and five (5) additional tests should be added for each additional 5,000 square feet.

4.4.2.2 Evaluation of Infiltration Testing Results

Soil infiltration rates can vary widely over short distances, even in soils that appear to be homogeneous. Measurements frequently exhibit lognormal statistical distributions, which are described using a geometric mean rather than the usual arithmetic mean. Therefore, when multiple tests are conducted the geometric mean of the data must be used to determine the average infiltration rate. The geometric mean of *n* numbers is the positive n^{th} root of their product, that is to say that the geometric mean of a data set $\{a_1, a_2, \ldots a_n\}$ is given by:

$$\{a_1, a_2, \ldots a_n\} = \sqrt[n]{a_1 * a_2 * \ldots a_n}$$

If results suggest there may be two or more distinct infiltration regimes additional investigation should be conducted to confirm this.

Example of Evaluating Infiltration Test Results

Assume three infiltration tests results are collected for a site. Infiltration rates were measured to be 0.35, 0.10, and 0.08 inches per hour. The geometric mean is calculated to be 0.14 in/hr based on the formula:

$$mean = \sqrt[3]{0.35 * 0.10 * 0.08} = 0.14$$

4.4.3 Soil Compaction

The most common approach to measuring compaction in the construction industry is the Proctor test (ASTM D698 Standard Proctor Test). The Proctor test defines the compaction rate as a percent of the soils maximum density at the optimum moisture level. In the field a nuclear densometer is used for the Proctor test. A nuclear gauge only reads compaction to the depth of the probe (typically 6 to 12 inches) and is only suitable for soils with less than 5% organic content. The Proctor test is a poor way of measuring compaction of soils bioretention areas and is not recommended.

A penetrometer measures the resistance as a probe is slowly pushed through the soil. The device provides instant readings of the relative soil compaction. Penetration resistance is affected by the soil type and soil moisture. Root growth decreases with increasing penetration resistance, until practically stopping above 300 pounds per square inch (psi). Soil placed to grow vegetation should have a penetration resistance reading of 75 to 200 psi with a soil moisture between 5 and 15 percent. The reading taken with a penetrometer are called the cone index. Measurements should be taken respective to recognizable compaction patterns. For example, if you know certain areas are used as walking paths, take transects in and out of the path and report them separately. The cone index values are likely to be quite variable, so multiple readings are required. It is recommended to take a minimum of three (3) readings per GI practice with at least one additional reading per 5,000 square feet.

4.4.4 Bulk Density

The bulk density of soil is the mass of a unit volume of dry soil. Bulk density is a measure of how tightly the soil particles are packed together, i.e., the amount of compaction. The amount of compaction affects the available pore space and rate of infiltration. Undisturbed natural forests and grasslands have a soil bulk density in the range of 0.8 to 1.1 g/cm^3. Soil bulk densities in the range of 1.4 to 1.7 g/cm^3 begin to limit the ability of plant roots to grow and penetrate the soil. Test methods for determining the bulk density of a soil are discussed in *Methods of Soil Analysis Part 4*.

4.4.5 Effective Porosity

What is the percentage of unfilled pore space in the soil usable for temporary stormwater storage?

Effective porosity is the void volume in soil available to temporarily store stormwater. *Effective porosity* is the difference between the *porosity* and the *field capacity*. Table 7 presents example test results from analyzing the soils in a bioretention practice in Lansing, MI. For the bioretention practices sampled, the results indicate an average effective porosity of 21%, meaning that 21% of the soil volume is pore space available to temporarily store stormwater. The effective porosity is a function of the soil type and level of compaction. Documenting the effective porosity for different soil mixes provides better information for use in design and when calculating the total storage volume for reporting purposes.

Porosity refers to the volume of voids contained within a given soil sample volume and is typically expressed as a percentage. The formula for determining the porosity is the volume of voids divided by the total volume of the soil sample. As soils are compacted, bulk density increases, and the porosity of the soil decreases. Porosity may be calculated if the particle density and the dry bulk density are known.

Porosity is closely related to the void ratio, which is widely used in soil mechanics. Void ratio is defined as the volume of the voids divided by the volume of the solids.

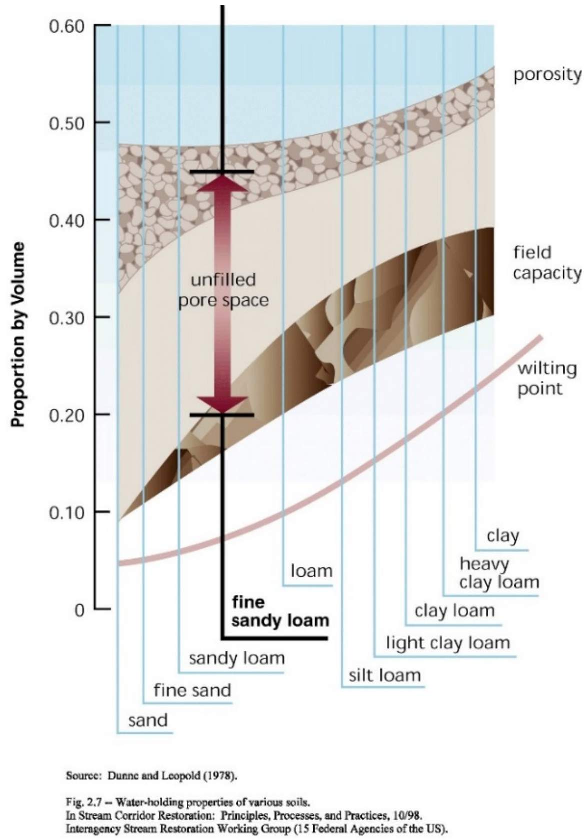


Figure 10 Water Holding Properties of Soils

While porosity determines the overall amount of pore space in the soil, soil pores occur in a variety of shapes and sizes that influence how water and air move through and are stored in the soil. The size, shape and interconnectedness of the pore network has a much larger effect on water movement and storage through soil than overall porosity does. The larger pores, called macropores, allow for drainage of water, movement of air, and spaces for roots and animals to move through the soil. Smaller pores, called micropores, are able to retain water after drainage. Much of the water used by plants is stored in the larger of these micropores.

Porosity may be estimated if the soil texture is known. Porosity may also be estimated from soil information in the USDA Web Soil Survey or by using the SPAW software a particle size analysis test is run on a soil sample. Test methods for determining the porosity of a soil are discussed in *Methods of Soil Analysis Part 4 by Flint and Flint* (2002).

Field capacity is the amount of soil moisture or water content held in the soil after excess water has drained away due to gravity. Moisture remaining is held in place due to the capillary action. Field capacity may be estimated if the soil texture is known. Field capacity may also be estimated from soil information in the USDA Web Soil Survey. Test methods for determining field capacity are discussed in *Methods of Soil Analysis Part 1 by Cassel & Nielsen* (1986).

Plants may remove water from their rooting zone and the soil will continue to dry below field capacity. Plants cannot remove all the water from the soil due to how tightly some water is held to the soil particles due to attractive forces. The term ***wilting point*** is used to describe the point at which plants cannot remove water from the soil fast enough to meet their needs, i.e., they begin to wilt. Test methods for determining field capacity are discussed in *Methods of Soil Analysis Part 1 by Cassel & Nielsen* (1986).

Table 7 Example Soil Test Results (Lansing)

Bioretention Garden	Location within the garden	Bulk Density (g/cm^3)	Porosity (%)	Field Capacity (%)	Effective Porosity (%)
700 block south side (#33)	East	1.06	52.4%	31.3%	21.1%
	Center	1.18	48.6%	29.7%	18.9%
	West	1.20	43.2%	27.5%	15.7%
800 block south side (#43)	East	1.17	49.2%	25.8%	24.5%
	Center	1.25	46.5%	25.8%	20.7%
	West	1.29	45.7%	25.8%	19.9%
700 block north side (#14)	East	1.08	57.8%	27.9%	29.8%
	Center	0.89	62.5%	40.5%	22.1%
	West	1.05	49.2%	31.6%	17.6%
Average		**1.13**	**50.6%**	**29.5%**	**21.0%**

4.4.6 Soil Moisture

Soil moisture is a measure of how much water is present in the soil at the time of measurement. Soil moisture is an important variable when measuring infiltration with some test methods (Modified Philip-Dunne) and for compaction. Soil moisture content changes significantly with time and must be tested in the field. Moisture content in existing soil can be measured by an array of portable instruments, which give moisture in percent or relative wet/dry scales. They generally work on the principle that more moisture passes greater amounts of electricity. The readings from these instruments may be skewed by high amounts of salt and other chemicals in the soil.

To measure the rise and fall of the amount (or percentage) of water in the soil, a *water content sensor* (also referred to as a *soil moisture sensor*) is used. To understand the availability of water for plants, plant water stress, or water movement (if water will move and where it will go), a *water potential soil sensor* is required in addition to a soil moisture sensor. Water potential is a measure of how tightly water is bound to soil surfaces and determines if water is available for uptake by roots.

4.4.7 Evapotranspiration

Evapotranspiration is the process by which water is transferred from the land to the atmosphere by evaporation from the soil (and other surfaces) and by transpiration from vegetation. ET is highly variable and depends on many factors such as the ambient relative humidity, amount of water available, and the vegetative cover. The most common approach to measuring ET from a stormwater BMP is to use a weighing lysimeter. A weighing lysimeter is essentially a scale used to measure the mass of an enclosed vegetated soil volume. Water from precipitation and runoff flows into the lysimeter. ET is then determined by completing the water balance within the control volume defined by the lysimeter boundary. ET may also be estimated from mathematical models such as the Penman-Monteith equation. Mathematical models for ET are often data intensive and may require monitoring information.

4.5 VEGETATION

The presence of vegetation plays a critical role in a bioretention system. Some questions that might be considered regarding bioretention vegetation include:

What is the overall health of the planted community?

Are there any trends in plant species survival/health?

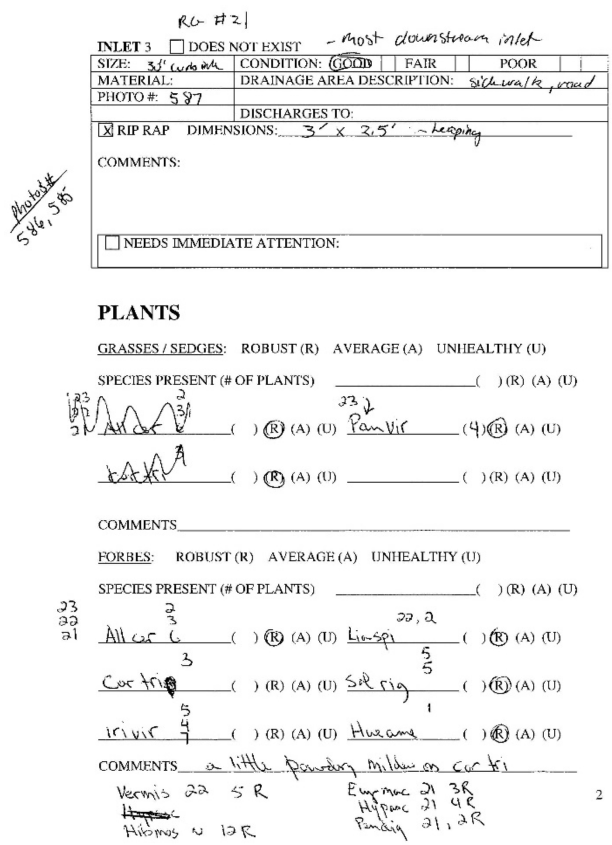
What plant species are recommended for replanting specific bioretention systems?

Is there any correlation between the following and the health of the plants: condition of the soil, the thickness of the mulch, the presence of weeds, or the presence of trash/debris?

The assessment process for vegetation involves an inventory of what plant species are present where and the health of the vegetation. Additional information such as the presence of trash and debris, and whether erosion is observed is also recommended at the time of the vegetation assessment. The following is suggested assessment information to be recorded:

- Quantification of each grass, forb, and tree species present
- Qualitative assessment of each plant species (robust, average, unhealthy)
- Spread or decline of species relative to the area initially planted.
- Pervasiveness of weeds (absent, few present, excessive)
- Condition of the soil (good, excessively dry, excessively wet)
- Degree of erosion (none, some, excessive)
- Degree of soil compaction (normal, excessive)
- Thickness of mulch (good, too thick, too thin)
- Pervasiveness of trash/litter (absent, normal, excessive)
- Overall aesthetics

Photographs should be taken during the assessment to provide record information and may be used to roughly verify quantities tallied on the assessment. Plant and garden health assessment information along with the existing plant quantities should be compared to the as-built drawing quantities or to a previous assessment result and recent maintenance logs.


INLET 3 ☐ DOES NOT EXIST

SIZE: | CONDITION: GOOD | FAIR | POOR

MATERIAL: | DRAINAGE AREA DESCRIPTION:

PHOTO #: 587

DISCHARGES TO:

☒ RIP RAP DIMENSIONS: 3' x 3.5'

COMMENTS:

☐ NEEDS IMMEDIATE ATTENTION:

PLANTS

GRASSES / SEDGES: ROBUST (R) AVERAGE (A) UNHEALTHY (U)

SPECIES PRESENT (# OF PLANTS) ____( ) (R) (A) (U)

COMMENTS

FORBES: ROBUST (R) AVERAGE (A) UNHEALTHY (U)

SPECIES PRESENT (# OF PLANTS) ____( ) (R) (A) (U)

COMMENTS

2

Figure 11 Example Vegetation Assessment Form

Figure 12 Vegetation Assessment

4.6 PAVEMENT SURFACE LAYER (POROUS PAVEMENTS)

What is the infiltration rate through the pavement?

Does the pavement need to be cleaned?

ASTM standard test methods are available for infiltration testing of permeable unit pavers and pervious concrete pavements. Permeable unit pavers include interlocking concrete paving units, concrete grid paving units, and clay paving brick. Porous asphalt surfaces may utilize the same ASTM test method as pervious concrete. Table 8 provides a summary of infiltration test methods for pavements.

Table 8 Pavement Infiltration Tests

Name	Method	Pervious Concrete	Porous Asphalt	PICP
Surface Infiltration Rate of Permeable Unit Pavement Systems	ASTM C1781			✓
Surface Infiltration Rate of Pervious Concrete	ASTM C1701	✓	✓	
Simple Infiltration Test for Permeable Pavement	Described below	✓	✓	✓

To determine if a pavement needs maintenance a simple infiltration test method is available for rapid testing and categorizing the result. For this simple infiltration test, an 8-foot-long piece of 2x4 lumber is cut and framed into a square. Plumber's putty is then placed on the bottom of the wooden frame. The frame is then pressed against a flat part of the pavement surface and 5 gallons of water is dumped inside the frame in as short a time as possible. Once water starts being poured into the frame, the complete drawdown is timed. When no water is visibly noted, the test stops. Results of the test and resulting actions are summarized in Table 9.

Table 9 Simple Pavement Infiltration Test Results

Time it takes water to infiltrate	Condition	Type of Maintenance Needed
<30 seconds	Performing very well. No runoff ever expected.	None
30-90 seconds	Pavement exhibits modest sediment/debris collection. In most cases, the pavement is infiltrating sufficiently well.	None probably needed; but preventative cleaning should be considered.
90-300 seconds	Pavement is clogging; some runoff is probably occurring, but light rains are probably infiltrating.	Clean permeable surface with a regenerative air sweeper vacuum or equivalent.
>300 seconds	Pavement is clogged. Storm events are causing runoff.	Clean permeable surface with a vacuum street sweeper.

Figure 13 Simple Infiltration Test

4.7 AGGREGATE STORAGE LAYER

Aggregate storage layers should be checked during construction to ensure the correct aggregate is used. After the storage layer is covered with bioretention soil or a pavement layer, it is very difficult to inspect. Inspections are typically limited to visual observations for showing locations of settling or observations of the water level in underdrains and cleanouts. Proper filling and drainage of the system is best checked using a flood test and recording the change in water level over time in an observation port or in the underdrain.

What is the effective porosity of the aggregate storage layer?

The effective porosity is a function of the aggregate type. Documenting the effective porosity for different aggregates provides better information for use in design and when calculating the total storage volume for reporting purposes.

Determining the available temporary storage volume in an aggregate layer may be accomplished from some standard ASTM tests.

- ASTM C29 Standard Test Method for Bulk Density (Unit Weight) and Voids in Aggregates
- ASTM C127 Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate
- ASTM C128 Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate

4.8 SUBSURFACE STORAGE VAULTS

Subsurface storage vaults such as plastic arches, cubes, oversized pipes, and concrete vaults, may be visually inspected with cameras or in-person if the systems are large enough. Look for sediment accumulation in the pretreatment area (if included) and across the floor of the storage vault. Proper filling and drainage of the system is best checked by recording the change in water level over time with flow metering equipment. Relatively small storage vault systems can potentially be checked with a flood test from a fire hydrant but often these systems hold very large quantities of water.

Figure 14 Subsurface Storage Vault

4.9 CLEANOUTS AND OBSERVATION PORTS

Cleanouts and observation ports provide access to subsurface storage and the subsurface drainage system (underdrain) if provided. Cleanouts are typically connected to the subsurface drainage system. Observation ports are typically standalone vertical units not connected to other systems. These points of access are useful in observing the water levels when filling and draining the system. The ports may be fitted with a pressure transducer for recording water surface elevation data.

4.10 SUBSURFACE DRAINAGE (UNDERDRAINS)

Subsurface drainage systems (underdrains) are often useful in monitoring the discharge from the green infrastructure practice. Depending on the configuration, they may also be used to measure the hydraulic grade line in the practice as well. When flow restriction devices such as outlet orifice plates and valves are used on the underdrain monitoring is typically done downstream of the restriction due to access limitations. Video inspection of the underdrain may be used to check pipe alignment, shape, joint connections, signs of sediment intrusion, and root intrusion.

If a GI practice with an underdrain is not properly draining the recommended first step is to check the underdrain for the discharge flow rate and a video inspection inside the underdrain. If the inside of the underdrain looks good but very little water is trickling through, then the outside of the underdrain needs to be checked. Checking the outside of the underdrain involves digging a test pit and exposing the underdrain system. Often the cause is associated with a geotextile clogging.

Figure 15 Bioretention Not Draining

4.11 SUBGRADE

What is the infiltration rate into the subgrade below the green infrastructure practice?

Measure infiltration based on subgrade soil conditions. During the design phase, test pits should be dug to measure the subgrade infiltration. The subgrade should be checked during construction as well. The infiltration tests during construction are used to establish a baseline condition. After construction is complete the subgrade infiltration may be tested using a flood test and temporarily blocking subsurface drainage systems and other outlets. The change in hydraulic grade line may be observed in cleanouts, observation ports, or sometimes in the outlet control structure.

Infiltration test results are used to adjust the parameters of an infiltration equation such as Horton or Green-Ampt. The same infiltration equation is then used during the rain event to quantify the loss of water due to infiltration.

Subgrade infiltration can also be determined as a part of the water balance based on monitoring the inflow and direct discharge.

Figure 16 Subgrade Infiltration Test

4.12 OBSERVATION WELLS

Observation wells may be placed around a green infrastructure practice to monitor the groundwater table. This is useful for looking at the groundwater mounding near the green infrastructure practice and for determining the groundwater movement. Wells are typically fitted with pressure transducers to record the water depth.

4.13 OUTLET

How much water is leaving the green infrastructure practice?

What is the relationship between the water depth in the practice and the rate of water leaving the practice (stage-discharge)?

Outlet monitoring is essentially the same as inlet monitoring. Concentrated flow streams are monitored by selecting the appropriate primary and secondary flow measurement equipment. Sheet flow conditions are typically monitored as weir flow at the upstream end or by channelizing the flow at the downstream end.

Figure 17 Bioretention Washout

Outlets often have multiple control structures, e.g., an orifice or valve for the low flows through the underdrain and weirs handling larger flows from the surface. Care must be taken when positioning the monitoring equipment to get accurate measurements. Multiple meters may be required. Alternatively, moving the monitoring equipment downstream a manhole from the outlet control structure may provide a single metering location with uniform flow conditions. Long-term monitoring projects should consider the addition of a dedicated monitoring location for the outlet control.

Outlets should be observed visually after major rainfall events for signs of washout of sediment, mulch, and other debris. Overflow conditions from project sites should also be considered when designing a monitoring plan, i.e., during severe rain events where is the water going to go.

4.14 OVERFLOW

Water spilling over the sides of the GI practice or other uncontrolled releases of water during large storm events is considered ***overflow***. This also includes sheet flow off pervious pavement surfaces. Ideally, the system should be designed to avoid this situation. If this does occur either a reasonable estimate of the overflow is needed (e.g., assume weir flow exiting over the sides) or the event should be excluded from the net change calculations.

Note: some type of monitoring information is needed in order to know if this is occurring. For example, a pressure transducer in the middle of the GI practice to measure the depth of water. Detailed elevation information is needed of the surrounding area to compare it to the water depth in the GI practice. Video or time-lapse photography can also help quantify overflow discharge.

4.15 OTHER TYPES OF MONITORING

There is a plethora of non-hydrologic monitoring that can and is being done around green infrastructure practices. For example, there are studies focusing on the social interaction, economic impact, habitat creation, flora and fauna, and soil health, as well as chemical, biological and physical pollutants studies.

5.0 RAINFALL AND FLOW MONITORING EQUIPMENT

Accurate collection and analysis of hydrologic and hydraulic data is essential for monitoring and assessing the performance of GI. To begin with, precipitation and other meteorological data are key to characterizing the hydrologic conditions. Accurate measurements characterize the runoff into, out of, and stored in a GI practice. Consider all the various pathways water can enter and leave a stormwater practice. For example, is all the influent through a pipe or is there runoff enter as overland flow? There are many choices to consider when selecting monitoring equipment. This section discusses some of the considerations and flow ranges for evaluating equipment choices.

5.1 RAINFALL

Precipitation monitoring is essential for any hydrologic study project. Precipitation data helps characterize rainfall events such as the total rainfall amount, the intensity, duration, and when the rainfall started and stopped. When combined with the tributary drainage area and land cover characteristics, flows may be calculated to compare against monitored data.

There are several different types of rain gauges including graduated cylinders, tipping buckets, weighing gauge and optical rain gauge. Graduated cylinders require manual measurement and recording of the data and are not recommended. The other types of rain gauges can be connected to a data logger and can record continuously.

Rain gauges typically need to be installed at the study site unless other nearby gauges are readily available. Generally, if the nearest rain gauge is over a mile away, then a dedicated rain gauge should be installed at the study site. When selecting a location for a rain gauge, vertical obstructions such as buildings and large trees are a major concern. As a general rule, the rain gauge should be located twice as far from the obstruction as the obstruction is tall. Other concerns during installation include: leveling the device, guarding against vandalism (elevate the unit), discouraging birds from perching, and being aware of possible influences of wind around buildings. The rain gauge collection funnel should be checked regularly for obstructions, e.g., spider webs, insects, leaf litter and other debris.

5.2 FLOW MEASUREMENT

Stormwater flow through BMPs is typically in an *open channel flow* state. From a hydraulic engineering perspective o*pen channel flow* condition is when the water surface is free (or unconstrained) and the flow is driven by gravity. *Open channel flow* conditions occur in ditches and channels, but also occur in sewer systems. Conversely *closed conduit flow* conditions are when the flow completely fills the conduit and flow is driven by a hydraulic pressure gradient, e.g., potable water transmission. The measurement of *open channel flow* rates is more difficult to obtain than *closed conduit flow* since the water depth will vary with time. *Open channel flow* measurement techniques are the focus of this section; however, some closed channel flow measurement techniques are also touched on. Most stormwater drainage systems (sewers, ditches, swales, gutters, curb-cuts, etc.) operate under the principles of *open channel flow*.

Stormwater flow rates vary significantly based on the rainfall and tributary watershed characteristics. Small, frequently occurring storm events account for the majority of runoff in the urban areas and are often the focus of the specific BMP. However, the municipal collection system is typically designed to convey larger, less frequent storm events such as the 10-year event. It is important that measurement devices be able to accurately monitor a broad range of flow conditions.

5.2.1 Primary Device

Accurate flow measurement relies on the use of both a primary and secondary device. The primary flow measurement device consists of a structural device used to constrict or otherwise control flow at the measurement point. Primary devices allow the determination of flow based on the measurement of the upstream head (stage or depth) acting on the structure. Primary devices can be large and bulky, and often have limited operating ranges. The best approach is to plan for primary devices during the design phase of a project and often install primary devices during construction. The most commonly used primary flow measurement devices include:

- Weirs
- Flumes
- Orifices
- Pipes

Each type of primary device is described below followed by a discussion of how to select a primary measuring device (page 42).

5.2.1.1 Weirs

Weirs come in all different shapes and sizes. The most common weirs are rectangular, trapezoidal (or Cipolletti), and triangular (or V-notch) weirs. Each type of weir has a specific discharge equation for determining the flow rate. Compared to flumes, weirs are generally low in cost, easy to install, and can be quite accurate when used correctly.

The stream of water leaving the weir crest is called the nappe. When air flows freely beneath the nappe, the nappe is said to be aerated and the flow is referred to as free or critical. When the downstream water level rises to the point where air does not flow freely beneath the nappe, the nappe is not ventilated resulting in changes to the flow characteristics which lead to inaccurate discharge rates. When downstream water levels rise to the crest of the weir, the weir is said to be submerged. Flow rates under submerged conditions can be determined by measuring both the upstream and downstream depths. In most cases weirs should be sized and installed to obtain free (ventilated) conditions.

The discharge rate is determined by measuring the vertical distance from the crest of the weir to the water surface upstream from the crest. To avoid sensing the localized water surface drawdown effects due to the weir, the head measuring point should be located upstream of the weir a distance equal to 3 to 4 times the maximum head expected over the weir (Figure 18).

Table 10 provides summary characteristics of the most common types of weirs. The minimum head required for accurate flow measurements is 0.2 feet. In water depths less than 0.2 feet, the nappe clings to the weir crest and reduces the measurement accuracy. Contained within the table is the recommended flow range for each type of weir. The flow range is calculated from the reported equations and is based on the minimum and maximum heads.

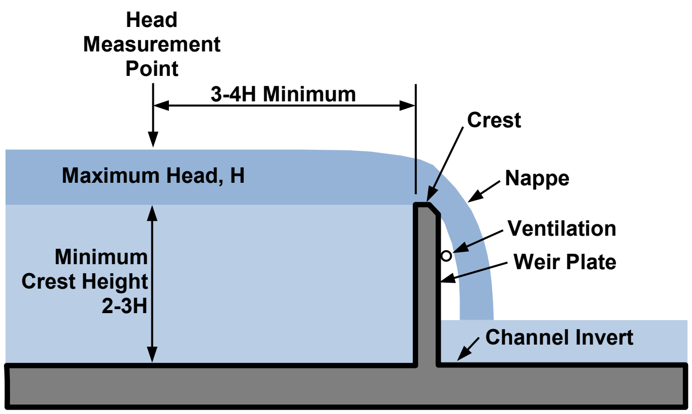
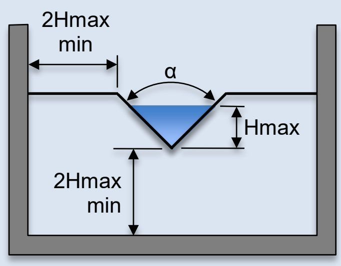
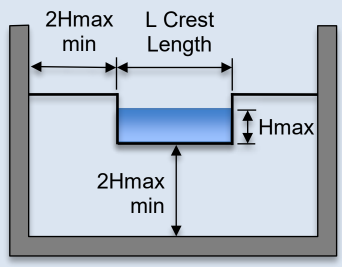
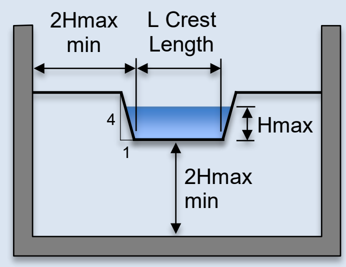


Figure 18 Weir Flow

Table 10 Weir Characteristics

Type	V-Notch (triangular)	Rectangular	Cipolletti (trapezoidal)
			
Notch	90 deg most common, other angles may be used	Min. L = 1.0 ft (use V-notch if L<1.0 ft)	Min. L = 1.0 ft (use V-notch if L<1.0 ft) End inclinations are at the ratio of 4 vertical to 1 horizontal
Side Offset	Minimum distance is 2Hmax	Minimum distance is 2Hmax for weir with end contractions	Minimum distance is 2Hmax
Vertical Offset	Minimum distance is 2Hmax	Minimum distance is 2Hmax	Minimum distance is 2Hmax
Minimum Head	0.2 ft	0.2 ft	0.2 ft
Maximum Head	2.0 ft	0.5L	0.5L
Equation	$Q = KH^{2.5}$ Q (cfs); H (ft)	$Q = K(L - 0.2H)H^{1.5}$ with end contractions $Q = KLH^{1.5}$ without end contractions Q (cfs); L (ft); H (ft)	$Q = KLH^{1.5}$ Q (cfs); L (ft); H (ft)
Coefficient	Angle, α / K: 22.5° / 0.4970 30° / 0.6760 45° / 1.035 60° / 1.443 90° / 2.500 120° / 4.330	K = 3.330	K = 3.367

Recommend flow range	α (deg)	Qmin (cfs)	Hmax (ft)	Qmax (cfs)	L (ft)	Qmin (cfs)	Hmax (ft)	Qmax (cfs)	L (ft)	Qmin (cfs)	Hmax (cfs)	Qmax (cfs)
	22.5°	0.009	2.0	2.81	1	0.286	0.5	1.06	1	0.301	0.5	1.19
	30°	0.012	2.0	3.82	1.5	0.435	0.75	2.92	1.5	0.452	0.75	3.28
	45°	0.019	2.0	5.85	2	0.584	1.0	5.99	2	0.602	1	6.73
	60°	0.026	2.0	8.16	3	0.882	1.5	16.5	3	0.903	1.5	18.6
	90°	0.045	2.0	14.1	5	1.48	2.5	59.2	5	1.51	2.5	66.6
	120°	0.077	2.0	24.5	10	2.97	5.0	335	10	3.01	5	376

Comments	Well suited for low flows	Recommended flow range provided for rectangular weir with end contractions	Less accurate than a rectangular or v-notch weir

Another variety of useful weirs are flow metering inserts specially designed to install in round pipes (or sewers). Commercially available weir inserts include round, v-notch and Thel-Mar weirs. A Thel-Mar weir is a compound weir with a V-notch profile on the bottom and rectangular profile with end contractions on the top. These flow metering insert weirs typically come with mounting rings to hold them in place in the pipe and are often available with an attached bubble tube. Table 11 provides flow ranges for commonly available weir insert sizes.

Table 11 Weir Inserts

Pipe Diameter (in)	V-Notch Flow Range (cfs)	Round Orifice Flow Range (cfs)	Thel-Mar Flow Range (cfs)
6	0.002 to 0.201	0.011 to 0.401	Up to 0.071
8	0.002 to 0.357	0.022 to 0.714	Up to 0.192
10	0.002 to 0.513	0.045 to 1.07	Up to 0.362
12	0.002 to 0.714	0.089 to 1.43	Up to 0.559

Figure 19 Thel-Mar Weir

5.2.1.2 Flume

Another major type of primary measuring devices is a flume. A flume is a specially shaped open channel section that restricts the channel area. The flow rate through the flume may be determined by measuring the head (depth) at a single point. A flume can measure a higher flow rate than a comparable weir and it can operate with a smaller loss of head compared to a weir. Because of the relatively high velocities, flumes tend to be self-cleaning and minimize solids depositions. Flumes tend to be larger and more expensive than weirs. Flumes often have strict requirements on the installation slope and are best installed during construction. In general, a flume is used to measure flow in an open channel where the use of a weir is not feasible.

Parshall Flume. Best known and most widely used, particularly for permanent installations. Sized based on throat width; minimum width 1 inch. Minimum head required is 0.10 feet for throat widths up to 18-inches; minimum head required increases as the throat width increases. Maximum head allowed is typically around 2.5 feet. The discharge equation through a Parshall flume takes the form:

$$Q = KH^n$$

Where: *Q* is the *flow* rate (ft^3/sec), *H* is the *head* (ft) measured in the throat of the flume, and *K* and *n* are *flume coefficients* based on the throat size. Refer to Table 12 for flume coefficients and the recommended range of flows.

Table 12 Minimum and Maximum Recommended Flow Rates for Parshall Flumes

Throat Size (in)	Flume Coefficient K	Flume Coefficient n	Head Minimum (ft)	Flow Minimum (cfs)	Head Maximum (ft)	Flow Maximum (cfs)
1	0.338	1.550	0.10	0.010	0.70	0.194
2	0.676	1.550	0.10	0.019	0.80	0.478
3	0.992	1.547	0.10	0.028	1.10	1.15
6	2.06	1.580	0.10	0.054	1.50	3.91
9	3.07	1.530	0.10	0.091	2.00	8.87
12	4	1.522	0.10	0.120	2.50	16.1
18	6	1.538	0.10	0.174	2.50	24.6
24	8	1.550	0.15	0.423	2.50	33.1
36	12	1.566	0.15	0.615	2.50	50.4
48	16	1.578	0.20	1.26	2.50	67.9
60	20	1.587	0.20	1.56	2.50	85.6
72	24	1.595	0.25	2.63	2.50	103
96	32	1.607	0.25	3.45	2.50	140

Figure 20 Flume Installation

Palmer-Bowlus Flume. Primary application is in pipelines or other round bottom open channel flow applications. May be installed in existing conduit since it doesn't require a drop in the conduit invert as would be required with a Parshall flume. Palmer-Bowlus flume sizes are designated by the size of pipe into which they fit. Thus, an 8-inch Palmer-Bowlus flume is designed to be inserted into an 8-inch diameter pipe. The minimum head required is 0.04 feet for flumes up to 10-inch and increase to 0.3 feet for a 72-inch flume. Example flow range for a 6-inch flume is 0.01 to 0.5 cfs; and 0.02 to 2.9 cfs for a 12-inch flume. The disadvantage is that they have a smaller useful range of flow rate compared to a Parshall flume. A Parshall flume produces a greater change in head compared to a Palmer-Bowlus flume.

Figure 21 Palmer-Bowlus Flume (12-inch)

Table 13 Minimum and Maximum Recommended Flow Rates for Palmer-Bowlus Flumes

Size (in)	Head Minimum (ft)	Head Maximum (ft)	Flow Minimum (cfs)	Flow Maximum (cfs)
4	0.04	0.31	0.004	0.180
6	0.04	0.47	0.006	0.512
8	0.04	0.63	0.008	1.06
10	0.04	0.78	0.009	1.84
12	0.05	0.94	0.019	2.89
15	0.06	1.17	0.027	5.29
18	0.08	1.31	0.050	6.97
21	0.09	1.53	0.067	10.2
24	0.10	1.76	0.096	14.4
27	0.11	1.97	0.029	17.6
30	0.13	2.19	0.131	24.7
36	0.15	2.63	0.246	39.9
42	0.18	3.07	0.389	55.0
48	0.20	3.39	0.532	75.0
60	0.25	4.24	0.783	165
72	0.30	5.08	1.42	393

H-type Flume. H-type flumes were originally developed for agricultural applications and are capable of monitoring flow over a wide range with reasonably good accuracy. H-type flumes differ from Parshall and Palmer-Bowlus flumes because they are more weir-like than a true flume. A rectangular approach channel is preferred, having the same depth and width as the flume. The downstream end of the H-type flume should allow for a free discharge, like a weir. HS, H and HL flumes are designated according to the maximum depth attainable in the flume. The HS flumes were designed to measure relatively small flows (0.085 to 0.821 cfs). The H flumes were designed to measure medium flow rates (0.347 to 84.5 cfs) H-type flumes come in a wide range of sizes. The HL flume were designed to measure larger flows (20.7 to 117 cfs). The discharge equation through a H-type flume takes the form:

Figure 22 HS Flume (1-ft)

$$Q = KH^n$$

Where: *Q* is the *flow* rate (ft³/sec), *H* is the *head* (ft) measured in the throat of the flume, and *K* and *n* are *flume coefficients* based on the flume size. Refer to Table 14 for flume coefficients and the recommended range of flows.

Table 14 Minimum and Maximum Recommended Flow Rates for H-Type Flumes

Type	Flume Size (ft)	Flume Coefficient K	Flume Coefficient n	Head Minimum (ft)	Head Maximum (ft)	Flow Minimum (cfs)	Flow Maximum (cfs)
HS	0.4	0.64	2.22	0.02	0.4	0.0002	0.085
HS	0.6	0.71	2.22	0.02	0.6	0.0002	0.229
HS	0.8	0.77	2.22	0.02	0.8	0.0003	0.470
HS	1.0	0.82	2.22	0.02	1.0	0.0004	0.821
H	0.5	1.71	2.31	0.02	0.5	0.0004	0.347
H	0.75	1.85	2.31	0.02	0.75	0.0006	0.957
H	1.0	1.95	2.31	0.02	1.0	0.0007	1.97
H	1.5	2.11	2.31	0.02	1.5	0.001	5.42
H	2.0	2.23	2.31	0.02	2.0	0.001	11.1
H	2.5	2.33	2.31	0.02	2.5	0.002	19.4
H	3.0	2.41	2.31	0.02	3.0	0.002	30.7
H	4.5	2.60	2.31	0.02	4.5	0.003	84.5
HL	4.0	5.01	2.27	0.02	4.0	0.005	117

There are many other types of flumes which have been developed to meet special design criteria or to solve a specific problem.

5.2.1.3 Orifice

An orifice is a hole or opening through which water flows. Orifices are commonly used to control discharge from basins and constructed wetlands where a specific detention time, water level, or maximum allowable discharge is desired. The basic equation of flow through an orifice is given by:

$$Q = C_o A\sqrt{2gh}$$

Where, C_o is the *coefficient of discharge*, A is the *area of the orifice* (ft^2), g is the *gravitational acceleration* (32.2 ft/s^2), and h is the *head* (ft) above the centroid of the orifice. In the case of a submerged orifice, h is the difference of the water surfaces upstream and downstream of the orifice. The coefficient of discharge (C_o) may vary as a function of head. For square-edged uniform orifice entrance conditions a discharge coefficient is typically taken as 0.6. For ragged edged orifices, such as those resulting from the use of an acetylene torch to cut the orifice opening(s), the coefficient is closer to 0.4. A stage-discharge curve can be calibrated for the orifice where flows can be measured.

Table 15 shows example flow ranges for various sized orifices. The range of flow for an orifice is relatively small. Multiple orifices may be installed to increase the total flow. In the case of multiple orifices, flows are calculated for each orifice and then summed together for the total flow rate. Partially filled orifices behave hydraulically like a weir. Small orifices are prone to clogging from debris in the flow stream.

Table 15 Example Flow Ranges for Orifices

Orifice Diameter (in)	Head Minimum (ft)*	Flow Minimum (cfs)	Flow (cfs) at 1-ft of Head	Flow (cfs) at 2-ft of Head	Flow (cfs) at 4-ft of Head
0.25	0.01	0.0002	0.002	0.002	0.003
0.5	0.02	0.001	0.007	0.009	0.013
0.75	0.03	0.003	0.015	0.021	0.030
1	0.04	0.005	0.026	0.037	0.053
1.5	0.06	0.015	0.059	0.084	0.118
2	0.08	0.030	0.105	0.149	0.210
3	0.13	0.084	0.236	0.334	0.473
4	0.17	0.172	0.420	0.594	0.840
6	0.25	0.473	0.945	1.34	1.89

*Minimum head is when the orifice is flowing full, i.e. the head is half the diameter

5.2.1.4 Pipe

The simplest primary device to select is often the open channel conveyance geometry itself. In urban areas this is often a pipe. The secondary measuring device may be installed to directly measure flow in the pipe. The minimum head and flow are often dictated by the secondary device. It's not uncommon to need approximately an inch of water in a pipe before accurate flow measurements can be achieved.

The flow rate (Q) in an open channel may be calculated from the cross-sectional area (A) and the average velocity (V).

$$Q = VA$$

The flow rate in an open channel when the flow is being moved by the force of gravity only (i.e., not under pressure) may be calculated based on Manning's equation.

$$Q = \frac{C_1}{n} A R^{2/3} S^{1/2}$$

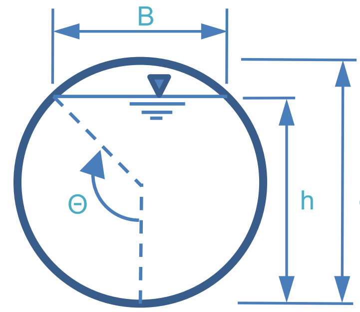
Where *Q* is the *flow* rate (cfs), c_1 is constant depending on units (1.486 for flow rates in cfs), *n* is a *roughness coefficient* dependent on the channel material, *R* is the *hydraulic radius* (cross section area divided by the wetted perimeter) and *S* is the *slope of the hydraulic gradient*. The *Manning roughness coefficient* (*n*) is often assumed to be constant when in fact it varies as a function of depth and may be important during low flow measurements. The *slope of the hydraulic gradient* is often assumed to be the slope of the pipe. When the slope of the pipe is assumed to be the hydraulic gradient, the depth measurement needs to be taken far enough away from the ends of the pipes to influence the flow conditions.

For a partially filled round pipe the area and wetted perimeter may be calculated from:

$$\theta = \cos^{-1}\left(1 - \frac{2h}{d}\right)$$

$$A = \frac{d^2}{4}(\theta - \sin(\theta)\cos(\theta))$$

$$P = \theta d$$



Where *h* is the *head* or depth of water in the pipe, *d* is the *diameter of the pipe*, and Θ is the angle between a vertical line in the lower half of the pipe and line extending from the center of the pipe to the water surface at the perimeter (radians).

5.2.1.5 Selecting a Primary Measuring Device

At the core of the monitoring plan is to understand the purpose of the flow measurements. Through the purpose, the range of expected flows and accuracy of measurements may be deduced. Also, of importance is if surcharged or flow reversal is likely. Selection of the primary measuring device is based on the range of flow conditions to be monitored, the required accuracy, the possibility of surcharged or reverse flow conditions and, lastly, budgetary constraints.

As a starting point, the expected range of flows along with the likelihood of flow reversals and surcharged conditions should be estimated based on typical engineering estimations. Begin by delineating the tributary drainage area and calculate the maximum flow expected. Let the purpose of the flow measurement help to select the rainfall condition for the maximum flow estimation. For example, if the purpose is to measure flow rates during a 10-year storm event, then the maximum flow might be something more than a 10-year storm. Whereas if the purpose is to measure the flow rate during typical summer storms, then a peak flow based on a 1- or 2-year storm event might be enough. A similar approach should be taken for the minimum flow estimation. If the goal is to quantify large storm events, then the minimum flow may not be important. However, if the goal is to consider dewatering times or measure flow rates based on very small rainfall events, then having the ability to accurately measure very low flows may be very important. Once the expected range of flows is known, then the tables and equations for weirs, flumes, orifices and pipes can be used to identify primary devices that may work.

Table 16 Summary of Advantages and Disadvantages of Primary Flow Devices

Device	Advantages	Disadvantages
Weirs	• Low cost • Easy to install • Easy to verify • Accuracy generally better than ±10% when properly sized and installed • Easier to install a temporary weir in an existing drainage system than a flume	• Fairly high headloss • Susceptible to clogging • Accuracy affected by excessive approach velocities
Flumes	• Self-cleaning (to an extent) • Relatively low headloss • Easy to verify • Accuracy generally ±3-5% when properly sized and installed	• High costs • Difficult to install • Installation often requires large structures to house the device and needs to be included during design and construction
Orifice	• Low cost • Easy to install	• Low range of discharges • Very high headloss • Easily clogged
Pipe	• Usually the pipe is already present, hence no cost • Easy to verify	• Low flow conditions are hard to measure • Accuracy generally ±10-20%

In some instances, multiple devices may be required to adequately measure the complete range of flows and conditions desired. It is important to note that if flow reversals or surcharged flow conditions are expected, these conditions often require technology that measure the level, direction and velocity of the flow stream. In some cases, the use of two level-sensors may be used.

5.2.2 Secondary Device

A secondary device consists of instrumentation used to determine flow or velocity based on measurements taken at the primary device. Thus, a combination of the primary and secondary device is required to measure flow. Common secondary flow measurement devices include:

- Submerged pressure transducer
- Bubbler
- Ultrasonic
- Area-velocity meter

5.2.2.1 Submerged Pressure Transducer

A submerged pressure transducer measures the hydrostatic pressure of the column of water above the sensor. The pressure is then converted to a depth of water. Submerged pressure transducers are not affected by wind, turbulence or floating debris. Submerged pressure transducers can be affected by changes in the water temperature and debris hitting the transducer because the transducer is installed in the flow stream. Some probes have a built-in thermometer to measure the water temperature and compensate for temperature fluctuations. Periodic maintenance is required to clean the probe. The probe must be submerged in the flow stream, hence there is a minimum required depth of water.

5.2.2.2 Bubbler

A bubbler also measures the hydrostatic pressure of water like a submerged pressure transducer. The difference is that an air tube is installed in the flow stream and the pressure transducer in a bubbler is located inside the meter which is mounted above the water level. Bubbles of pressured air are released from the end of the air tube.

The pressure transducer measures the pressure required to maintain the bubble rate and converts this to a water depth. Bubblers should not be used when the flow velocity exceeds 5 to 6 feet per second (approximately 5 to 7 percent channel slope) because a low-pressure zone is induced around the bubbler tube. Bubblers are not affected by water temperature. Periodic maintenance is required to remove accumulated silt and debris from the end of the air tube, however, periodic air purges may minimize the problem. Maintenance is required to prevent moisture from being drawn into the air system.

5.2.2.3 Ultrasonic

Ultrasonic sensors are mounted above the flow stream and transmit a sound pulse that is reflected to the sensor from the water surface. By knowing the distance, the sensor is mounted above the invert of the flow stream, the water depth is calculated. Ultrasonic sensors must compensate for changes in air temperature and typically have built-in temperature probes. The sensors are typically installed in sheltered applications rather than being exposed to sunlight or the outdoor environment because of concerns with temperature. Ultrasonic systems are not affected by water temperature or debris in the flow stream but may provide inaccurate results from floating debris and turbulence.

5.2.2.4 Area-Velocity Meter

Area-Velocity (AV) meters simultaneously measure the velocity and depth of the flow stream. Depth is converted to a cross-sectional area by knowing the channel geometry. Flow is then calculated by the channel cross-sectional area times the average velocity. A variety of area velocity flow technologies exist. The various sensor technologies are comprised of ultrasonic (Doppler), electromagnetic, and dynamic pressure methods. Some AV meters are installed in the flow stream and others are installed above the flow. Equipment installed in the flow stream requires periodic maintenance to clean the probe, is subject to damage from debris in the flow stream and requires a minimum depth of water to record accurate measurements.

6.0 EXAMPLE SITE

Shown in Figure 25 and Figure 26 is an example bioretention system set up for monitoring. In this case the bioretention is accepting drainage from the street and the practice is set back behind the sidewalk. Water from the street is directed into the bioretention through inlet system. The bioretention practice is an offline configuration, meaning that when the practice is full of water it backs water up on the street to continue to the traditional catch basin inlet. The monitoring set up for this site includes:

Rainfall. A rain gauge is located onsite as far away from vertical obstructions as possible to minimize measurement errors. A basic tipping bucket rain gauge was used (ISCO GR-8)

Sediment Pretreatment is provided at MH1. This minimizes the sediment and floatable debris entering the bioretention and potential fouling of the monitoring equipment.

Inflow. Inflow monitoring equipment was installed in MH2. For this study an ISCO 2150 AV Meter was installed along with a Thelmar 12” Compound Weir with Telog Pressure Transducer. Two pieces of equipment were selected because as the bioretention fills with water the inlet piping system fills with water and normal flow conditions no longer apply. The Thelmar weir was used for small flows and the AV meter was used for the higher flows. MH2 was added to the practice design specifically for monitoring the inflow to the bioretention

Bioretention Water Depth. A pressure transducer (Telog PT-3VF-10) was installed in the cleanout located in the middle of the bioretention. This was used to measure the water depth throughout the bioretention.

Direct Discharge. Flow exiting the system through the underdrain pipe was monitored at MH3 which is located between the bioretention and the receiving sewer. A backflow preventer is located downstream of the outflow monitoring to guard against surcharge from the collection system backing up into the bioretention. In this case a flume and pressure transducers were selected (12” HS-Flume w/PT-3 Pressure Transducer). This bioretention system has no outlet other than the underdrain pipes.

Figure 23 Flume Installation

Groundwater. This site included three groundwater monitoring wells for looking at the groundwater mounding effect. Monitoring wells were 15 feet deep and each contained a pressure transducer (Telog PT-3V-10 Pressure Transducer)

Photographic. The site was equipped with a motion-activated trail camera. The camera has a slight delay between the time a motion is detected and when the photograph is taken. The camera utilizes infrared lighting to take pictures during the night. It captured interesting aspects of the project site and offers insight to a range of topics including vandalism, the public’s interaction with the bioretentions, maintenance activities, and wet weather events.

Figure 24 Motion Activated Trail Camera

Receiving Sewers. Of concern at this location was the possibility of the bioretention garden causing an increased inflow/infiltration (I/I) in the sewer near the bioretention. Area-velocity meters were installed in the sewer system upstream and downstream of the bioretention.

This monitoring study considered many issues including:

- Inlet efficiency
- Infiltration rate of water through the bioretention media
- Infiltration rate of water into the subgrade

- Optimum valve setting (the underdrain includes a valve)
- Peak flow reduction
- Volume reduction
- Total water managed
- Volumetric runoff coefficients
- Groundwater reaction to rainfall
- Groundwater mounding adjacent to bioretention
- Public interaction with bioretention

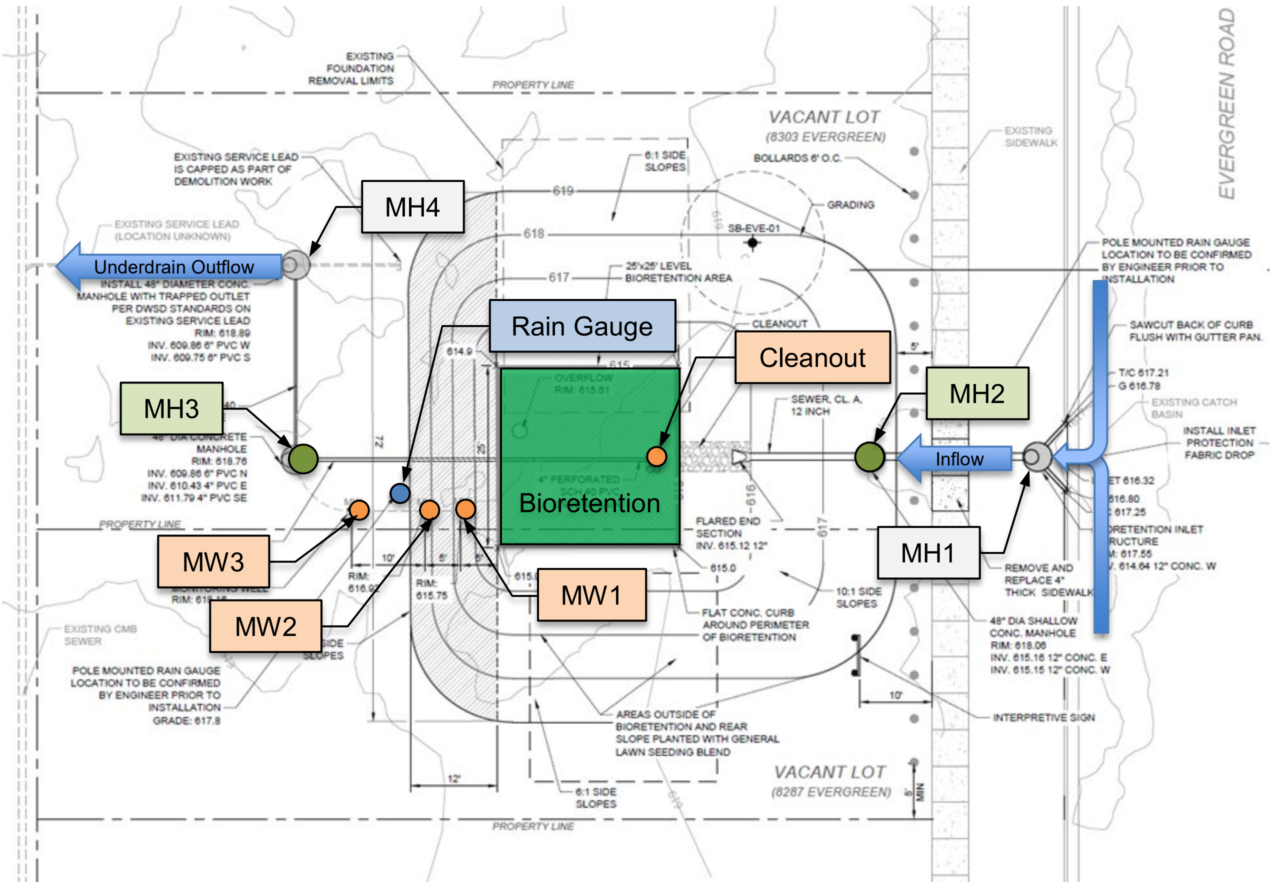


Figure 25 Example Bioretention Site for Monitoring Plan View

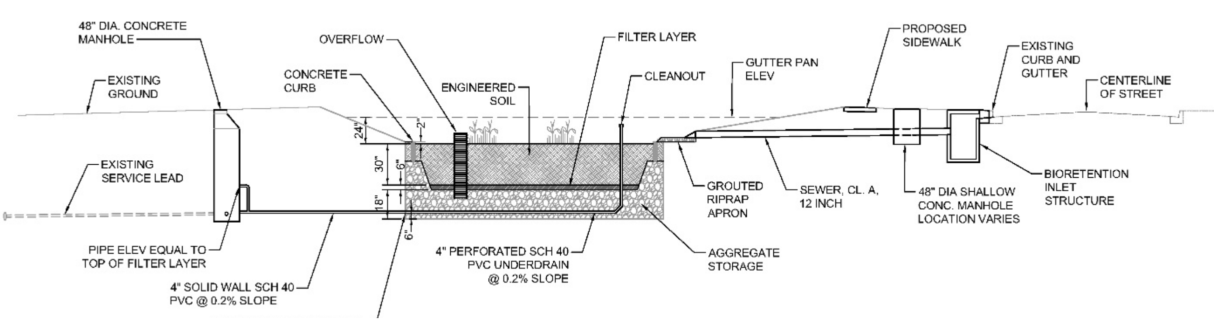


Figure 26 Example Bioretention Site for Monitoring Cross Section

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