Pittsburgh Regional Green Stormwater Infrastructure Monitoring Guidebook Prepared by The Pittsburgh Water and Sewer Authority

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List of Acronyms

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Monitoring Committee Members:

Tom Batroney, Hatch Mott McDonald

Barton Kirk, Ethos Collaborative

Molly Mehling, Chatham University

John Buck, Civil and Environmental Consultants, Inc.

Dan Bain, University of Pittsburgh

Tony Igwe, Wade Trim

Beth Dutton, 3 Rivers Wet Weather

Costa Samaras, Carnegie Mellon University

Damon Weiss, Ethos Collaborative

Duygu Altintas, Carnegie Mellon University

Emily Elliott, University of Pittsburgh

Erin Copeland, Pittsburgh, Parks Conservancy

James Stitt, PWSA

Jeanne VanBrisen, Carnegie Mellon University

Katherine Camp, PWSA

Michael Finewood, Chatham University

Sara Powell, Nine Mile Run Watershed

Timothy Prevost, ALCOSAN

Gina Cyprych, PWSA

Lisa Vavro, Penn State Center

Marion Sikora,

Matt Graham, Landbase Systems

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Section 1.0 – Introduction

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1.1 History of Regional Combined Sewer Overflow and Regulatory Requirements

The Pittsburgh Water and Sewer Authority (PWSA) and the City of Pittsburgh have a responsibility to manage its water resources in compliance with the Federal Clean Water Act and the State's 1937 Clean Stream Law. Pittsburgh, like many cities across the country, has a combined sewer system with aging pipes and infrastructure that are unable to effectively convey sewage and stormwater runoff to the water treatment plant during rain events over 1/10" of precipitation. These events result in combined sewer overflows (CSO) and sanitary sewer overflows (SSO) which discharge directly into Pittsburgh's rivers and streams. CSO and SSO events bring the City out of compliance with its regulatory agencies.

In 2004, the Pennsylvania Department of Environmental Protection (PaDEP) and the Allegheny County Health Department (ACHD) issued a Consent Order to the City of Pittsburgh and PWSA to address both CSO and SSO events. Concurrently, in 2008 ALCOSAN, the entity responsible for processing PWSA's sewage entered a Consent Decree with the Environmental Protection Agency (EPA), the Department of Justice, ACHD and PaDEP to develop a Wet Weather Plan to addressing CSO and SSO events by January 2013.

As part of the Wet Weather Plan development and implementation, PWSA believes that incorporating cost effective and strategically placed green stormwater infrastructure runoff source reduction practices should be part of the solution to CSO and SSO events. Green stormwater infrastructure (GSI) refers to a variety of strategies designed to mitigate stormwater runoff and associated pollutants through infiltration, evapotranspiration, and/or detention. Some examples of these strategies include: green surface storage strategies such as rain gardens, bioswales, or stormwater wetlands; subsurface storage features such as infiltration trenches or porous pavement installations; or rooftop strategies such as green roofs or blue roofs.

In addition to CSO and SSO reduction benefits as part of the Consent Order agreements, GSI is also capable of providing additional benefits such as increased protection from hazardous flooding events and improved water quality benefits from pollutant removal, temperature reduction, and ground water recharge.

PWSA has a history of working with local environmental nonprofits, foundations and regulators to better assess, plan for and implement GSI strategies across Pittsburgh. The purpose of this manual is to provide general guidance for monitoring GSI strategies. .

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1.2 The Importance of GSI Performance Monitoring

PWSA recognizes the importance for demonstrating the effectiveness of GSI at a localized level in the Pittsburgh region. The success of the GSI is often dependent upon localized factors such as regional climate and weather patterns, soil conditions, and topography. Understanding how these unique factors specific to the Pittsburgh region influence the performance of various GSI strategies is critical to its long term success. It is important to demonstrate and prove that GSI will be effective for the Pittsburgh region's unique conditions of localized factors.

Understanding the true effectiveness of GSI can only be determined through effective monitoring practices and data collection. Unfortunately monitoring is never a one size fits all due to the complexities of various GSI strategies. For each GSI strategy, the capabilities of the available monitoring equipment and the equipment's appropriate placement must be carefully considered. In some instances, it is advantageous to properly incorporate monitoring equipment and placement during the design phase of the GSI facility prior to construction. Forward planning of monitoring equipment during design phase often creates a more conducive condition for accurately collecting monitoring data at the GSI facility.

This manual provides general guidance for designers, regulators, and agencies for incorporating monitoring into GSI facilities.

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1.3 PWSA Green Infrastructure Monitoring Technical Committee and Approach

In 2013, PWSA assembled a Green Infrastructure Technical Advisory Committee (GITAC) to assist PWSA in addressing technical challenges related to GSI implementation. PWSA and the GITAC, recognizing the need to address monitoring, created a Monitoring Sub-Committee. The following sections outline the subcommittee and its objectives.

Committee Goals and Objectives

The GITAC Monitoring Sub-Committee is a combination of technical practitioners, researchers, scientists and government entities with technical expertise and interest in improving stormwater management in the Pittsburgh region. Compliance with federal and state regulations is the basis for creating monitoring protocol but the committee acknowledges the holistic aspects GSI can achieve beyond just water quality compliance issues. PWSA's GITAC Monitoring Sub-Committee drafted 10 GSI monitoring goals with the ideal time of achievement.

1. Prove Post Construction Compliance for Combined Sewer Overflow (CSO) Consent Order (2021)
2. Provide a Driving Mechanism for Adaptive Management within the Integrative Watershed Planning Initiative of PWSA's Long-Term Wet Weather Control Plan (LTCP) (2016)
3. Prove Compliance for Municipal Separated Sewer Systems (MS4) and current Total Maximum Daily Load (TMDL) Requirements (2016)
4. Inform the GSI Technology Verification Process for Future Stormwater Utility (2016)
5. Guide Conditions / Agenda for Partnership with other Organizations on Shovel Ready Projects (2015)
6. Prove Compliance for future TMDLs and NPDES permit requirements (unspecified)
7. Understand the full value GSI provides PSWA and the communities it serves (unspecified)
8. Understand the operations and maintenance requirements for best management practices (unspecified)
9. Evaluate lifespan of facilities (unspecified)
10. Drive and inform the development of GSI design standards (2015)

In order to achieve the ten objectives stated above the Monitoring Subcommittee recognized the need for GSI monitoring data and outlining appropriate protocols in a GSI Monitoring Manual. Participants of the Monitoring Subcommittee developed an outline for the manual and assigned various members sections of the manual for authoring. This manual is a compilation of each of those sections.

The GITAC Monitoring Sub-committee acknowledges that no single monitoring effort can, by itself, be used to define performance of a GSI practice. However, it can contribute to the growing body of research on these practices, which will help define their effectiveness in protecting and restoring the Pittsburgh region's valuable aquatic resources from the impacts of sewer overflows and the land development process. The results of individual monitoring efforts

can also be used to improve the way that green infrastructure and stormwater management practices are designed and maintained.

The GITAC Monitoring Sub-Committee recognizes that monitoring data collected can be used to:

- Document the performance of commonly used practices
- Document the performance of new or innovative practices
- Document the effectiveness of these practices in removing local pollutants of concern (e.g., total suspended solids, nitrogen, bacteria) from post-construction stormwater runoff
- Evaluate the effectiveness of specific GSI design features (e.g., aquatic benches, vegetated forebays, stone chimneys)
- Evaluate how local conditions (e.g., regional climate patterns, soil conditions, topography) influence performance
- Determine whether or not the performance of GSI in the Pittsburgh region differs from the performance of GSI practices used in other physiographic regions
- Provide a scientific basis for future development, modification or revision of local wet-weather control plans, land development and redevelopment code.

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National GSI Monitoring Case Studies and Research

The Pittsburgh Regional GSI Monitoring Guide Book draws on a body of stormwater research and technical guides developed over the last three decades. Much of the content is directly adapted from previously developed GSI monitoring documents, including the following:

- U.S. Environmental Protection Agency's 2009 *Urban Stormwater BMP Performance Monitoring Guide*
- U.S. Environmental Protection Agency's 2012 *CSO Post Construction Compliance Monitoring Guide*
- U.S. Environmental Protection Agency's 2014 *Greening CSO Plans: Planning and Modeling Green Infrastructure for Combined Sewer Overflow (CSO) Control*
- Center for Watershed Protection's 2009 *Coastal Stormwater Management Practice Monitoring Protocol*
- Technology Acceptance Reciprocity Partnership *Protocol for Stormwater Best Management Practice Demonstrations* (updated 2003)
- Chesapeake Stormwater Network's *Technical Bulletin 10. Bioretention Illustrated: A Visual Guide for Constructing, Inspecting, Maintaining and Verifying the Bioretention*

GSI performance data is still limited especially in regards to specific site conditions in a wide range of geographic locations. (Kiparsky, 2015). Increasing the amount of data collected and analyzed on GSI installations both national and globally will better inform designers and implementers about the parameters of certain site conditions, associated installation and maintenance costs and overall performance. Learning from previous installations will allow for more design standardization which will ultimately make GSI more cost effective for municipalities.

The International Stormwater Best Management Practice Database (ISBMPD) and the National Pollutant Removal Performance Database are the primary clearinghouses for individual GSI practice performance studies. While both contain a significant amount of data for over 500 projects, but several groups of GSI practices have small data samples in either of the databases and a majority are not located in Pittsburgh region. The only way to fill in these data gaps is to establish a comprehensive approach to monitoring and a collaborative sharing of the results.

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Section 2.0 – Pre-Condition Monitoring and Hydrologic Characterization

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2.1 The Importance of Pre-Condition Monitoring

The objective of performing pre-condition monitoring is to characterize the hydrologic stormwater runoff response of the catchment prior to the construction of the proposed GSI facility(s). Characterizing the pre-condition stormwater runoff response prior the construction of GSI is important because it provides a representation of the baseline non-GSI conditions of the catchments. The data collected from pre-condition monitoring baseline allows for a direct hydrologic performance comparison of the catchment with and without GSI. Section 3.0 outlines a general approach for implementing a pre-condition monitoring at proposed GSI facilities.

2.2 Step-by-Step General Approach for Pre-Condition Monitoring

The development of a pre-condition monitoring study would generally follow these steps:

1. Define the contributing drainage area of catchment to the proposed GSI
2. Understand the neighboring sewer piping network and hydraulics servicing the GSI
3. Identify required monitoring equipment based on site conditions
4. Prepare a pre-installation monitoring plan
5. Install monitoring equipment and perform regular maintenance
6. Collect the data and perform QA/QC
7. Perform data analysis
8. Quantify stormwater runoff reductions

The following describes each of the steps for implementing a pre-condition monitoring study. Generally it is recommended that pre-condition monitoring take place 6-months prior to the beginning of construction of the proposed GSI facility to allow for sufficient time frame for hydrologic characterization.

Step 1: Define the Contributing Drainage Area

Typically, the delineation of the contributing drainage area for the proposed GSI is done during the initial design phase. Therefore, this value is typically known prior to the consideration of a pre-condition monitoring study. However, the general procedures for determining the contributing drainage area are outlined in this section in the event the drainage area is unknown at the time of the pre-condition monitoring.

Defining the contributing drainage area is important for understanding the size and scope of the project area and the monitoring equipment that is most suitable. Defining the drainage area typically consists of conducting a desktop GIS analysis and verifying the desktop GIS analysis in a field investigation. Particular attention in the field investigation should be given to curb lines and other hydraulic barriers that may not be obvious from LiDAR and topographic mapping in the initial GIS analyses.

Conduct a Desktop GIS Analysis

When conducting a desktop GIS analysis, the first step is to identify the existing stormwater inlets and catch basins that service the proposed GSI. Once identified, the contributing areas of each of the inlets are delineated based upon existing contour data, aerial photography, and google street view (if available). Some typical rules of the thumb to follow when performing the GIS delineation analysis are as follows:

- Assume stormwater runoff travels perpendicular to the contour lines;
- Delineate the drainage area that contributes to each inlet based upon the individual land surfaces. For example, the area should be delineated and quantified individually based

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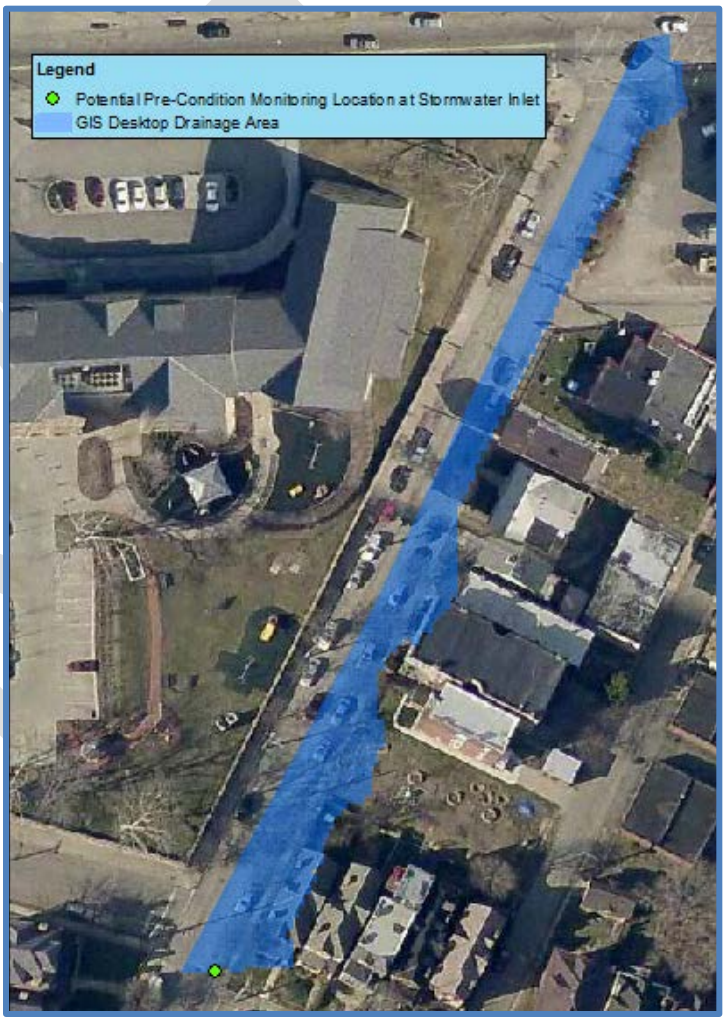
upon impervious surfaces (streets, parking lots, sidewalks, roofs, and driveways – each impervious area may also be delineated) and pervious surfaces (areas such as lawns and wooded areas);

- Consider general engineering drainage principles such as a center crown in roadways, 4-6" curbs along street edges, and sidewalks that are pitched toward the roadway;
- Roof downspouts are typically more difficult to determine from a GIS desktop analysis, and it is recommended to verify potential contributions from these sources by field investigations.

Verify Desktop GIS Analysis with Field Investigations

A field investigation should be performed using the desktop GIS delineated maps in hand. Typically the field investigation is performed during a precipitation event that produces enough stormwater runoff to be able to compare the flow break-lines and boundaries produced on the GIS desktop delineated map. The exact boundaries of contributing area should be confirmed and photos should be taken of areas to document any changes to the original GIS analysis. Photos are typically useful where drainage pattern uncertainties typically arise, such as within roadway intersections and parking lots. Dye tracer methods may also be performed to better ascertain exact flow patterns and contributing area boundaries in the field; employing the dye tracer method also helps project the image more clearly in the photos.



In addition to verifying the drainage patterns, field investigations should confirm all potential roof downspouts for their potential contribution to the stormwater inlets. Each external roof downspout should be identified on the GIS map and how each downspout is configured within the site (for example, drains to yard area, drains to garden area, drains to impervious area, connected to service lateral).

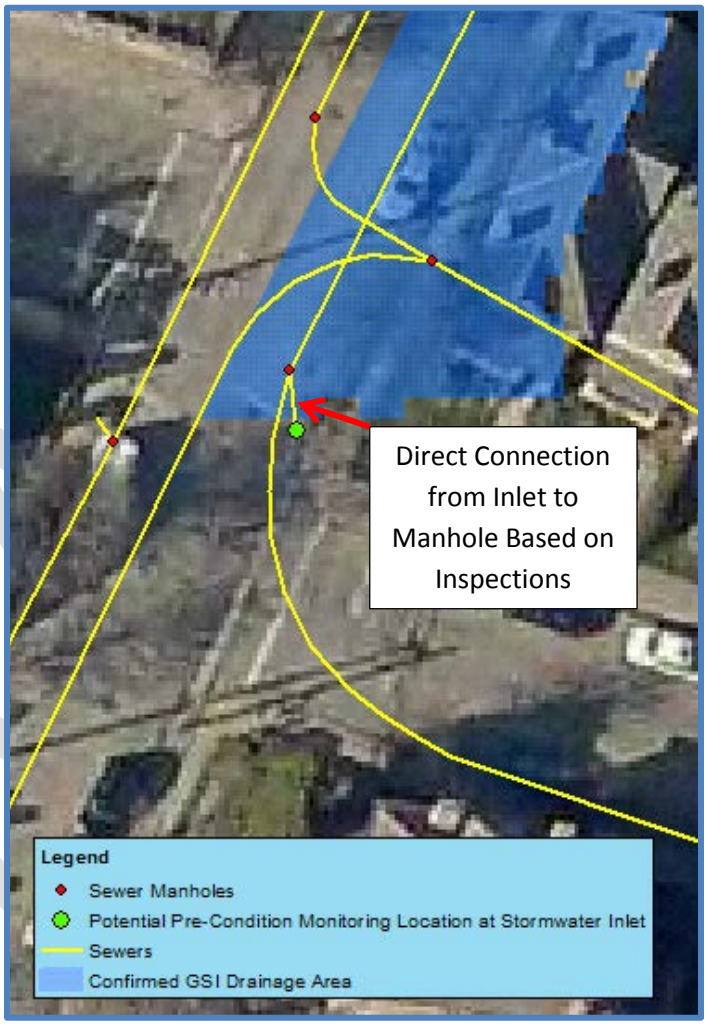
Step 1 Documentation:

Documentation of step 1 should be a short written document with a delineated map identifying the contributing drainage areas, neighboring roadways with labels, and neighboring structures

with locations of downspouts. The document should describe the field investigations performed along with the associated date and time of the investigations. Photographs taken should be identified and described to give the reader proper context and perspective. All roof downspouts should be identified on the map and their pre-condition configuration identified. Any other surface level drainage anomalies on the site should be documented and described (for example low lying ponding areas, presence of yard area drains, unconventional surface grading, etc).

Step 2: Understand the Neighboring Sewer Conveyance Network

The next step is to identify how the existing stormwater inlets and catch basins connect to the existing sewer conveyance network at the proposed GSI location. Having this understanding of the below ground piping network will allow for correctly identifying the proper selection and placement of monitoring devices. Each stormwater inlet within the GSI drainage area should be opened, inspected, measured and photographed to document the dimensions of the existing stormwater inlet and catch basin. The interior of the catch basin should be cleaned if excessive debris and sediment is present. The service pipe connecting the catch basin and the main conveyance sewer should be fully understood. The service pipe diameter, material, condition, slope(s), and connection configuration (for example, manhole tap or direct wye connection) to the main conveyance sewer should be documented. CCTV should be performed to identify the condition of the entire service pipe and the connection configuration to the main sewer.



Understanding how the service pipe is connected from the catch basin to main conveyance sewer is of critical importance to the selection and placement of monitoring devices. If the service pipe from the catch basin to main sewer connects via a direct manhole tap-in, flow monitoring devices can be installed at the either the inlet within the catch basin or the outlet at the location of the manhole tap-in. If the service pipe from the catch basin to main sewer connects via a direct wye connection, flow monitoring devices must be installed at the inlet within the catch basin. Direct wye connections present a more challenging scenario for accurate flow data collection.

The main conveyance sewer manholes residing within the GSI service area should be inspected for evidence of surcharging. Surcharging evidence includes water lines or rings on manhole walls or evidence of paper or debris on ladder rungs or the manhole lid. The level of the

surcharge should be measured from the manhole channel to the surcharge evidence elevation. Elevated surcharging may impact the performance of flow monitoring devices installed within the service sewer from the catch basin to the main sewer and it is important to document this evidence up front for future QA/QC of collected data.

Step 2 Documentation:

Step 2 documentation should include a short written document describing the service connections from the catch basin to the main conveyance sewer. The document should include:

- Dimensions of the catch basin;
- Condition of the catch basin and if cleaning was required;
- Dimensions and condition of the service pipe (include CCTV, if required);
- Connection configuration of the service pipe to the main conveyance sewer;
- Evidence (or lack thereof) of surcharging within main sewer manholes with associated measurements and photographs; and
- Include on a map the approximate locations the service sewer, main conveyance sewers, and manholes (preferably include on drainage area map in Step 1.)

Step 3: Identify Required Monitoring Equipment

To accurately characterize the pre-condition hydrologic stormwater runoff response of the proposed GSI location drainage area, the monitoring equipment needed primarily consists of nearby, high-resolution precipitation measurement and flow monitoring devices. The following list of monitoring equipment is often installed during pre-condition monitoring; for more detailed information on individual equipment refer to "GI Hydrologic Performance Monitoring Techniques and Equipment" in Section 3.0 of this manual. Below are some general guidelines on this equipment.

- Precipitation/Climate – To be located in an open area away from obstructions and wind shearing effect
    - Tipping Bucket Rain Gauge (heated requires power source) or
    - Optical Rain Gauge (requires power source) or
    - Climate Station – Precipitation along with air temperature, relative humidity, solar radiation, wind speed/direction and, optionally, barometric pressure sensors. Typically installed on light posts or street poles with solar panels. Optionally, leaf wetness sensors may be used to provide context as to antecedent surface wetness if refined estimates of initial abstraction are of interest.

- Flow Measurement Devices – To be located in the catch basin service line(s) in a favorable location with minimal turbulence and smooth laminar flows. Devices should be inspected during service to determine whether debris build-up has occurred since installation.
    - Area Velocity Meters - preferably Sigma 920, Isco 2150, or similar flow metering velocity Doppler technology with redundant ultra-sonic and pressure transducer depth capabilities and attached data logger, or
    - Flumes – Palmer Bowlus or H-Flumes (with pressure transducer and data logger), or
    - Weirs – Thel-Mar Weir or V-notch plate (with pressure transducer and data logger)

  The selection of the proper flow meter is largely dependent upon the connection configuration of the service sewer from the catch basin to the main sewer. In most

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cases, it preferred to have the selected flow measurement device at the outlet end of the service pipe. This will not be possible if the service sewer is directly connected to the main sewer with a wye connection or the outlet location at the manhole tap-in is structurally deficient or hydraulically unsuitable due to potential turbulence, steep pipe gradient, or evidence of consistent surcharging. Area-velocity meters are generally preferred over flumes and weirs due to potential presence of debris within the stormwater runoff and associated sensor fouling.

- Data loggers – May be standard operation or configured for wireless communication/real-time monitoring
- Deep groundwater monitoring devices (mounding effect)? Would be neat to compare groundwater response pre and post GSI. Drilling groundwater wells isn't cheap though. I think pretty disruptive as well.
- Soil moisture devices? Not really sure this is needed for pre-condition

Under most cases, water quality monitoring should not be performed prior to the installation of the GSI. Quantifying the effectiveness of pollutant removal of GSI should be done using both inlet and outlet water quality sampling within the GSI during the same storm event. It is not recommended to determine pollutant removal effectiveness of GSI using different storm events under different pre and post installation conditions and varying rainfall event patterns.

Step 3 Documentation:

Documentation of step 3 should be a short document describing the equipment selected with manufacturer and model identified and the location of the equipment. The document should include a brief description behind the reasoning. A maintenance and re-calibration schedule for the equipment should be included. The locations of the equipment should be included on a map (preferably include on map in steps 1 and 2).

Step 4: Develop a Pre-Condition Monitoring Plan

Based on the information gathered in Steps 1 through 3, a final pre-condition monitoring plan should be developed for review by the appropriate regulatory body (PWSA if in the City of Pittsburgh) and for future reference. Items within the plan should include, at minimum, the items listed under the documentation items for steps 1 through 3. Installation of equipment should not proceed until final approval of the monitoring plan from appropriate regulators.

Step 5: Install Monitoring Equipment and Perform Regular Maintenance

Selected precipitation monitoring equipment should be installed in an open area away from obstructions, potential wind shear effect from structures, and in a safe location away from potential vandalism and tampering. Flow measurement devices should be installed in a favorable location with minimal turbulence and smooth laminar flows. All data loggers on the proposed site should be configured using an identical time clock and day light savings time setting. Data logging for rain gages and flow monitoring devices should be at 5-minute intervals. Rainfall monitoring should clearly distinguish whether total liquid equivalent (rain + snow) precipitation is being measured, or only liquid rainfall.

Individuals responsible for installing any monitoring equipment in manholes and/or catch basins must be confined space entry trained individuals under OSHA required CONFINED SPACE SAFETY TRAINING complying with 29 CFR 1920.146. Whenever possible, monitoring methods that avoid confined space entries should be used.

Maintenance and re-calibration of the monitoring equipment should follow manufacturers recommended guidelines for the selected equipment and the schedules identified in the Pre-Condition Monitoring Plan. Generally it is recommended that rain gages are checked and cleaned of debris the collection funnel, checked for internal interference with moving parts by spiders and other insects, and checked for proper level mounting bi-weekly. The tipping bucket should be checked for accuracy with a volumetric cylinder with a controlled slow drainage rate at least annually. Flow metering devices are recommended to be checked and cleaned of debris bi-weekly and checked for depth accuracy monthly. Flow metering devices should be checked after very large storm events for operational status. Battery life on rain gages, flow meters, and data loggers should be checked on every field visit.

The total number of monitoring equipment devices is generally dependent upon the site conditions. Generally, one well-calibrated, well-maintained precipitation monitoring device in close proximity to the project is sufficient. The number of flow monitoring devices is generally dependent upon the number of catch basin service sewers on the proposed GSI site. Each catch basin service line impacted by the proposed GSI should be monitored with a flow monitoring device.

Maintenance records for all equipment should be kept in a standardized form and uploaded to the data sharing ftp folder or other centralized database upon completion of data quality checks.

Step 6: Collect Data and Perform QA/QC

Associated data loggers for the monitoring equipment may be standard manual download or may be configured with wireless telemetry for real-time monitoring capabilities. Standard manual download will require a durable laptop (including consideration of operation in bitter cold) for downloading the data upon each site visit; it is recommended that the data be downloaded and verified upon each site visit during regular maintenance activities (approximately every two weeks). Data loggers configured with wireless telemetry can be programmed to automatically download data at user defined intervals and insert the data into a pre-configured database. The pre-configured database may optionally include data quality screening against plausible data ranges and data variability criteria, and alerting systems to provide early notification of sensor and/or communication failures. The data may be then be extracted as an Excel-compatible file (csv, xls, txt) for further analysis and graphing.

Step 7: Perform Data Analysis

Data analysis for pre-condition monitoring primarily consists of describing the rainfall to runoff hydrologic response for each flow monitoring device within the catch basin service sewers. Typical calculation outputs from the analysis include:

- Rain event disaggregation based upon a user specified inter-event dry period;
- Individual rain event statistics such as event start and end times, event duration, total rainfall depth, peak rainfall intensity, frequency return interval of the storm, antecedent dry time from previous storm event, antecedent leaf wetness, if available, etc;
- Graphical storm event hydrographs; and
- Hydrograph based calculations such as peak flow, total volume, time to peak, time of concentration, and storm event “R-Coefficient” effective rainfall.

More information on Data Analysis Procedures is provided in Section 6.0.

Step 8: Quantify Runoff Reductions

The ultimate goal of the GSI monitoring program is to evaluate the effectiveness of constructed GSI installations at reducing stormwater runoff and water quality impacts entering the sewer

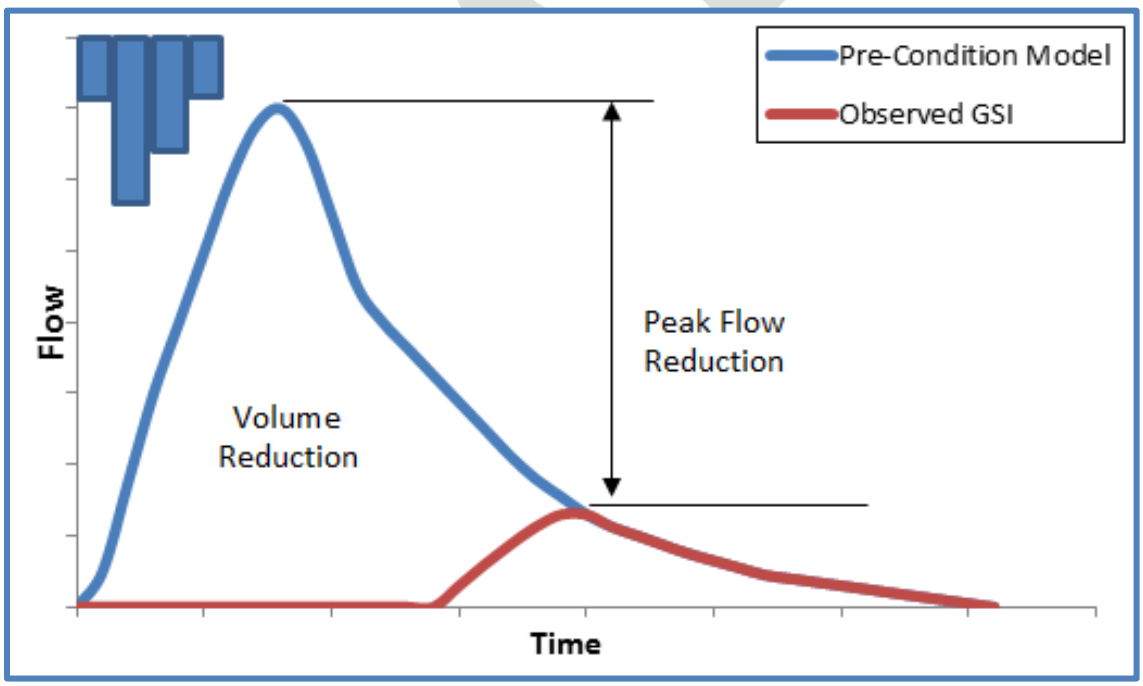
system. Unfortunately it is very rare that rainfall event characteristics and patterns during the post-installation GSI monitoring phase will match pre-condition monitoring data. The discrepancy in rainfall characteristics often leads to an “apples and oranges” comparison when comparing raw monitoring data for pre and post GSI installation. Two methods are presented below for comparing pre and post condition monitoring data to quantify runoff reductions.

Method 1: Develop Hydrologic and Hydraulic Model

Method 1 involves the development of a calibrated and validated EPA Storm Water Management Model (SWMM) of the catchment area using the pre-condition monitoring data. The model of the pre-condition catchment can then be simulated for observed rainfall events and a direct comparison of the hydrologic performance can be made between the GSI facility and the pre-conditions.

It is recommended that at least 3 rainfall events of varying event sizes are used for model calibration and at least 2 separate rainfall events are used for model validation. Guidelines within the Wastewater Planning Users Group “Code of Practice for the Hydraulic Modeling of Sewers” are recommended for assessing the overall statistical accuracy of the model during calibration and validation efforts.

The following hydrograph represents a graphical representation of how the pre-condition model would assess the performance of the stormwater entering the catch basin post GSI installation.



Using the results from the model, the volume and peak flow reductions can be quantified and directly applied to the larger SWMM model for the sewershed to determine resultant CSO benefits.

Method 2: Pre-Construction and Post-Construction Monitoring Direct Comparison Performance Reduction Assessment

Method 2 involves directly comparing pre and post condition monitoring data against each other by normalizing the flow data by the rainfall observed and the known drainage area. First the

runoff volume calculated under the hydrograph for each observed rainfall event for both the pre-construction and post-construction conditions. The runoff volume for each storm event should then be normalized by the respective total rainfall over the flow meter contributing drainage area. This value is often referred to as the “effective rainfall” or “R-Coefficient” of the drainage area. The R-Coefficients from pre-conditions from post-conditions can be statistically compared to determine the flow reduction benefits of the GSI facility(s).

R-Coefficient = [Runoff Volume Observed (cu ft) / Drainage Area (sq ft) * 12] / [Total Volume of Rainfall Observed (inches)]

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Section 3.0 – Site Scale GSI Hydrologic Performance Monitoring

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3.1 Importance of Individual GI Hydrologic Performance Monitoring

GSI monitoring can be discussed in terms of individual site scale monitoring as well as in terms of watershed scale monitoring that covers multiple GSI installations. This section discussion the general approaches for individual site scale GSI performance monitoring. Knowing the physical, biological and hydrologic processes of these systems is key in determining which GSI technology is appropriate for individual stormwater runoff situations.

Due to the variation in GSI designs and features, as well as rainfall distributions, there is not a one-size-fits-all monitoring strategy. For example, Pittsburgh receives approximately 38 inches of rainfall a year, primarily in small storms, whereas Austin receives approximately 35 inches of rainfall, but primary in large storms, whereas Denver receives approximately 14 inches per year. These differences in rainfall distributions affect both the design of GSI and the design of monitoring programs. Many GSI facilities are designed to treat runoff from small storms, rather than large storms, so it is important to understand the basis of design for GSI when developing monitoring programs and evaluating the performance.

Section 3.0 discusses:

- An overview of GSI typologies for appropriately selecting and locating monitoring equipment,
- GSI monitoring techniques and equipment,
- General example approaches for conducting site scale GSI monitoring,
- Periodic visual performance monitoring techniques, and
- Simulated rainfall performance tests using fire hydrants.

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3.2 Green Infrastructure Individual Monitoring Typologies

The EPA categorized the general types of GSI to assist in monitoring strategy design and performance analysis in the Urban BMP Monitoring Manual publication. These categories include:

Type I

GSI with well-defined inlets and outlets (e.g., detention basins, vegetated swales, catch basin inserts). These are the "easy" GSI types to monitor where inflow and outflow can typically be paired to assess performance. In the case of systems such as wet ponds with substantial residence times or storage volumes, data may be straightforward to collect, but challenging to evaluate for individual storms. In such cases, a seasonal mass balance approach is often more appropriate than a storm-based, paired influent-effluent approach because it is likely that the effluent sample for small storms is displaced water originating from prior events.

Type II

GSI with well-defined inlets, but not outlets (e.g., infiltration basins, infiltration trenches, bioretention cells). Monitoring strategies for these GSI types are more complex and may involve sampling of underdrains, vadose (unsaturated) zone monitoring, groundwater monitoring, measuring infiltration rates and surface overflow. At a minimum, the influent and surface overflow must be quantified, since the difference between the two should represent the volume infiltrated. If an underdrain is used to direct partially treated water back to the surface drainage, then it should also be monitored. Evaluation of data from these types of studies should focus on mass balance approaches.

Type III

GSI with well-defined outlets, but not inlets (e.g., grass swales where inflow is overland flow along the length of the swale, buffer strips, green roofs).

Type IV

GSI without any well-defined inlets or outlets and/or institutional technologies (e.g., buffer strips, basin-wide catch basin retrofits, education programs, source control programs, disconnected impervious area practices).

Type V

LID/Distributed Controls/Overall Site Designs where some defined monitoring locations are available that may include monitoring of individual practices within a development, in combination with an overall site monitoring mechanism.

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3.3 GSI Hydrologic Performance Monitoring Techniques and Equipment

Section 3.2 outlines various monitoring equipment often used for GSI monitoring. The section covers rainfall equipment, climate monitoring equipment, storage and level equipment, soil moisture and infiltration equipment, and data logging and communications equipment.

Rainfall Monitoring Equipment

Some form of rainfall monitoring equipment is essential in nearly all GSI monitoring studies. It is recommended that rainfall monitoring equipment be installed no less than a mile from the GSI, and it is often desirable to have the rainfall monitoring equipment directly adjacent to the GSI facility within ¼ mile in distance. Close proximity is recommended because rainfall patterns can vary significantly within a small geographic area due to orographic effects (i.e. weather variations due to hills and change in elevation) and climate related spatial variations. While there is no exact formal guidance on the distance the rainfall monitoring equipment must be in relation to the GSI facility, in general it is recommended that the rainfall monitoring equipment be placed as near as possible to the GSI facility. If monitoring a collection of GSI facilities over a large area, a standard guideline for rainfall monitoring equipment spacing is 1 mile. Ideally, rain gages should be located away from buildings, trees, or other over hanging objects that may affect measurements.

The following is an outline of available rainfall monitoring equipment typically used for GSI monitoring studies. Installation and maintenance of all rain gages below should follow individual manufacturer's recommended guidelines.

<u>Standard Rain Gage</u>

Standard rain gages (SRGs) are plastic or metal cylinders that are placed vertically in the ground to collect rainwater. These devices are typically read manually on a daily basis. The National Weather Service, for example, uses the 8-inch non-recording SRG as the primary rainfall measuring device at Cooperative Weather Stations.

A SRG consists of four major components: (1) measuring tube; (2) collector funnel; (3) measuring stick; and (4) overflow can. When it rains, an 8-inch collector funnel in the SRG directs rainfall into a measuring tube, which can range in capacity from 0.5 to 2 inches. The amount of water in the tube is measured using a measuring stick in the device, which is typically marked every one hundredth of an inch. When rainfall during an observation period exceeds the 2-inch capacity of the measuring tube, water spills from it into the overflow can. The capacity of the overflow can ranges from 7 to 20 inches. When using this device, it is important to manually read rainfall amounts promptly after an event to prevent underestimation due to evaporation from the SRG.

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For more precise GSI monitoring studies using short time increments, it is not recommended to use non-recording manual SRGs.

Manufacturers of SRGs include: High Sierra Electronics, Inc – Non Recording Rain Gage Model 2601-00

For more detailed information on non-recording standard rain gages visit the National Weather Service website here: http://www.weather.gov/iwx/coop_8inch

Tipping Bucket Gage

The operation of the tipping bucket rain gauge consists of collecting precipitation into a rain gauge funnel. As precipitation is collected in the funnel, it flows through a screen and is directed into a calibrated bucket. The bucket will tip when the correct amount of water volume is collected to the calibrated value (0.01 inches of rainfall.) As the bucket tips, the enclosed switch is tripped and is recorded on in internal data logger. The excess water is discharged through the bottom of the unit, and the process is repeated.

Tipping bucket rain gages can be either battery operated or directly connected to a standard AC power supply. Tipping bucket rain gages may be heated to prevent freezing and allow for the collection of frozen participation such as snow, sleet and freezing rain. Heated tipping bucket rain gages often require a direct AC power supply.

Tipping bucket rain gages are often complimented with standard manual rain gages to confirm tipping bucket accuracy. Sometimes during heavy intense rainfall events, the tipping bucket mechanisms can become overwhelmed resulting in under estimated rainfall values.

When using tipping bucket rain gages maintenance is important. The funnel should be periodically checked for debris and the tipping bucket mechanism inspected for functionality. The housing unit should be cleared from insects and spiders. Installation, calibration and maintenance procedures should follow manufacturer's recommendations.

There are numerous manufacturers of tipping bucket rain gages on the market. Some of these include: RainWise Inc., Global Water, and Campbell Scientific to name a few among many. Typical cost per tipping bucket rain gage is $500 to $1,000 depending on added features such as heating, data logging, and communications.

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Weighing Gage

A weighing precipitation gage collects precipitation data by directing precipitation into a storage bin, which is weighed to record the mass of the precipitation. Certain models measure the mass using a pen on a rotating drum, or by using a vibrating wire attached to a data logger. At a prescribed time interval (typically every few minutes), a recorder attached to the scale records the weight of the bucket contents. Unlike the tipping bucket gage, this gage does not usually underestimate intense rain events. Another advantage of a weighing gage is that it can collect measurements of hail and snow simply by filling the collection bucket with a pre-weighed volume of antifreeze. Weighing gauges are more expensive and require more maintenance than tipping bucket gages. Direct AC power is usually required on all weighing gages.

There are numerous manufacturers of weighing rain gages on the market. Some of these include: Belfort Instrument, OTT Pluvio², MicroStep-MIS to name a few among many. Typical cost per weighing rain gage is $2000 to $6000 depending on added features such as heating, data logging, and communications.

Optical Gage

Optical rain gages use a laser and phototransistor detector along with an array of collection funnels. As rain drops fall through the gap between the laser and optical detector, the amount of light hitting the optical detector is reduced. The variation in light intensity upon the optical detector is proportional to rainfall. Optical rain gages are highly accurate. However, the cost for

an optical rain gage ranges anywhere from $10,000 to $15,000. Manufacturers of optical rain gages include: All Weather Inc and Optical Scientific.

Piezoelectric Detectors

A new and unique approach for measuring precipitation is by using an acoustic sensor that measures the impact of individual raindrops on a smooth stainless steel surface using a piezoelectric detector. The sensor provides real time information on rain intensity, duration, and accumulated rainfall. Two advantages of this system is that it also has the ability to distinguish between rain and hail and the sensor has no moving parts or components that need emptying or cleaning resulting in less maintenance requirements. Currently Vaisala RAINCAP® Sensor Technology is the main provider for this relatively new precipitation monitoring technique. Preliminary results indicate that this new technology is as accurate as standard tipping buckets.

Climate Monitoring Equipment

Complete weather stations are commercially available as complete units that typically monitor an array of meteorological parameters. These parameters often include precipitation, temperature, humidity, wind speed and direction, and barometric pressure. Collecting full climate data at the GSI monitoring location can inform other hydrologic processes such as potential evaporation and rain wind shearing effects.

As with rain gages, the placement of weather stations is critical for the collection of representative and accurate data. The various climate sensors may need to be placed in different locations. For example, when collecting temperature and humidity, location should account for potential direct solar radiation and shade effects. It may be important to multiple sensors in and out of the shade to monitor heat changes due to shade. Anemometers (wind speed) and rain gages should be placed out in the open, away from obstructions that can block wind and prevent significant portions of rain from being collected by a rain gage. All climate stations require a direct power source to power the monitoring devices which can be hard wired into the station or supplied from attached solar panels.

In lieu of a full weather station, relatively inexpensive Thermochron “iButtons” or comparable devices can be attached to various locations to record temperature. These can be taped to telephone poles, weighted and placed in ponds and so on.

Climate station maintenance is usually done on an as-need basis. Data is typically accessible in real-time over the Internet, faulty sensor readings will be detected early. When this occurs, maintenance will need to be done assisted by a ladder to reach the climate station. Climate station maintenance is usually straightforward and will entail cleaning the radiation lens, calibrating rain gages, along with other wiring and programming work. There may come times when extreme hazardous weather conditions will require the equipment to be secured during the storm. This may require a team to take down the equipment prior to the storm. After the storm, equipment will need to be reinstalled.

Some examples of climate station manufacturers include: Campbell Scientific and Decagon Devices. Typical cost per climate station is typically around $3,000 to $10,000 depending on manufacturer and added features such as sensors selected, power supply options (solar panels), data logging and communications capabilities.

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Level Monitoring Equipment

The use of level monitoring equipment is often utilized in GSI facilities to determine height of water within storage reservoirs. This data is primarily useful for monitoring the filling and draining cycles within of the GSI facility throughout various seasons. The data can used for many purposes including monitoring the overall performance of the facility, signaling potential failures/required maintenance due to the facility not draining properly, determining flow rates through weirs and other flow conveyance structures, and extrapolating infiltration rates of the GSI facility using the "drawdown curve" from the collected data.

Level monitoring equipment often uses one of two technologies to measure level: 1.) pressure transducer or 2.) ultrasonic technology. For GSI installations it is not recommended to use ultrasonic technology due to leaf debris and the potential for false readings. Pressure transducer technology uses the density of the liquid and its height on the sensor. The liquid creates pressure on a

calibrated internal diaphragm within the sensor housing unit. The amount of pressure detected on the diaphragm is then converted into height of liquid above the sensor.

When selecting a pressure transduce level sensor it is important to know if the pressure transducer is capable of running dry. Some pressure transducers require constant submergence within a liquid for accurate data collection. Pressure tranducer level sensors for GSI facility monitoring should consider transducers that are capable of reading under dry un-submerged conditions. This is because there will be times when the GSI facility will be empty under dry conditions particularly during the summer months.

Pressure transducers are often installed in perforated PVC monitoring wells that allows for the water to enter and surround the sensor. Monitoring wells can be installed at varying locations and depths within the GSI facility to understand flucations in water level at desired locations. When installing the monitoring well it is important to understand the bottom of the well in relation to the GSI facility design. It is not desired for the well to be lower the bottom of the GSI storage layer. An accurate datum measurement of the bottom of the well in relation to the GSI storage area should be recorded prior to installing the pressure transducer.

Maintenance and calibration should follow manufacturer's recommended guidelines. Generally, maintenance of level sensors typically consists of cleaning the housing unit and replacing the dessicant. Calibration typically consists of checking for accuracy with a bucket a test and a ruler. A bucket or graduated cylinder is filled with water and the level sensor inserted. The measured depth of the water with the rule should match the output reading on the sensor. This check is typically performed on a monthly basis.

There are numerous manufacturers of pressure transducer level monitoring equipment. Some examples include: Campbell Scientific, Global Water, Telog Instruments, and Hach-Sigma. Typical cost per level sensor is typically around $700 - $1,500 depending on added features such as desired cable length, data logging and communications.

Soil Moisture and Infiltration Monitoring Equipment

Soil moisture sensors measure the volumetric water content in soil. Soil moisture sensors are often used in depth increments within the soil media and/or underlying native soil layer of the GSI facility. One of the primary advantages to measuring soil moisture content is the ability to determine the infiltration rate of the GSI facility. As a moisture front passes by the soil moisture sensor(s) a corresponding infiltration rate can be deduced and compared against other sensors in the same facility or neighboring facilities. This allows for the ability to identify the emptying performance of the GSI facility.

Soil moisture sensors utilize reflectometers to measure the passing moisture front as the soil moisture content changes due to infiltrating runoff. The measurement from the reflectometer is then transmitted to a data logger and recorded at user defined intervals. Many soil moisture sensors are also equipped to measure temperature simultaneously in addition to soil moisture content. In order to increase accuracy, soil moisture sensors are often calibrated to the known soil media in which the sensor will reside. Choosing the most appropriate sensor will consist of knowing the characteristics of the GSI facility soil media (often provided in spec sheets). For GSI facilities it is recommended that the soil moisture sensor technology is digital rather than analog. This is primarily due to the need for higher resolution accuracy as well as the need to measure temperature.

There are many manufactures on the market for soil moisture sensors including Decagon, AquaCheck, and Campbell Scientific. Typical cost for a single soil moisture sensor ranges depending on manufacturer and additional features such as temperature logging.

Open Channel Flow Monitoring Equipment

Quantifying flow volume reductions is often one of the primary objectives for conducting GSI monitoring. Several flow monitoring technologies are available on the market for use within GSI facilities. The configuration and type of GSI facility will dictate the most appropriate flow monitoring technology for implementation. The following section provides an overview of several flow monitoring technologies that are typically used at GSI facilities.

Weirs

A weir is a designed vertical structure placed across an open channel that allows water to flow through a flow rated notch. Weirs can come in the form of plates or manufactured weir boxes (typically used for connecting to circular pipes). There are many types of weir flow rated notch geometries that can be used to measure discharge. The three most common geometries of weir notches are: the rectangular, triangular, and trapezoidal. Each type of weir notch opening has a specific discharge equation for determining the flow rate through the weir opening. The notch openings can also be combined (for example, a weir can implement both a triangular and rectangular notch opening); these weir are often referred to as “compound” weirs.

The primary advantage to a weir is that it can be used to regulate flow in a natural channel with irregular geometry. Natural channels are often common occurrences within GSI facilities particularly within bioswales and constructed wetlands. Weirs collect flow measurements by creating a partial dam which results in backwater conditions upstream of the weir. The water will then pass over the weir to free-flow conditions on the downstream side of the weir. The flow rate is then calculated based on the geometry of the weir notch and recorded water level behind the weir.

When evaluating a GSI facility for the placement of a weir, it is important to determine expected flow rates and associated water levels for a range of expected rainfall events both upstream and downstream of the weir. If calculations indicate that the water level on the downstream side of

the weir is greater than the crest of the weir (i.e., the weir is submerged), a different stage-flow relationship for the weir will apply and flow calculations must be adjusted accordingly under these conditions. Generally, weirs are most effective in locations where there is no influence from potential downstream submergence. These are in areas where there is enough drop in head to convey flow through the GSI facility and over the flow monitoring weir.

It is important to note that when conducting a flow monitoring using a weir a water level sensor will also be required to record the level behind the weir in order to calculate the associated flow rates. See water level monitoring equipment above for more information on water level sensors.

There are numerous manufacturers of calibrated weirs on the market. Some examples of these manufacturers include: Openchannelflow, Rickly Hydrological Company, Park Environmental Equipment. Prices vary widely depending on the type and size of the weir.

Weir installation requirement calculations such as minimum approach length, maximum velocity and required slope will be necessary upon installation. These installation guidelines will vary depending on the manufacturer and weir geometry. The guidelines should be strictly followed in order to promote an adequate flow regime for accurately collecting level and flow data.

Maintenance of weirs of consists of cleaning the approach channel due to the settling of sediment particles above the weir, particularly during low flow conditions. Sediments and debris that accumulate behind a weir can alter the hydraulic conditions, changing the empirical relationship between flow depth and discharge rate. Weirs should be inspected regularly to remove accumulated sediment or debris. If high amounts of sediment or debris occur in the flow, then use of a flume may be more appropriate as flumes generally avoid sedimentation problems.

It is also important to check for signs of bypass flow and scouring around the sides of the weir structure. For accurate measurements all upstream flow should pass through the weir structure. If signs of bypass flows are present, it should be corrected immediately.

Flumes

Like weirs, there are many types of shapes and sizes of flumes for conducting open channel flow monitoring in GSI facilities. A weir and flume operate on the same hydraulic principles, where flow through a known geometric area is calculated using the recorded depth and a depth-flow rating equation for the flume. The water level through the flume is often monitored using a pressure transducer level sensor as described above. Using the recorded water level, the volumetric flow rate can be calculated based upon the manufacturer's provided flow rating equation. The rating equation is different based upon the type of flume selected and the size of the flume. A flume is typically chosen over a weir when there is potential for sedimentation impacts behind a weir. A flume does not have a flow restricting weir plate, and therefore is able to better convey sediment through the opening thereby minimizing maintenance and sensor fouling.

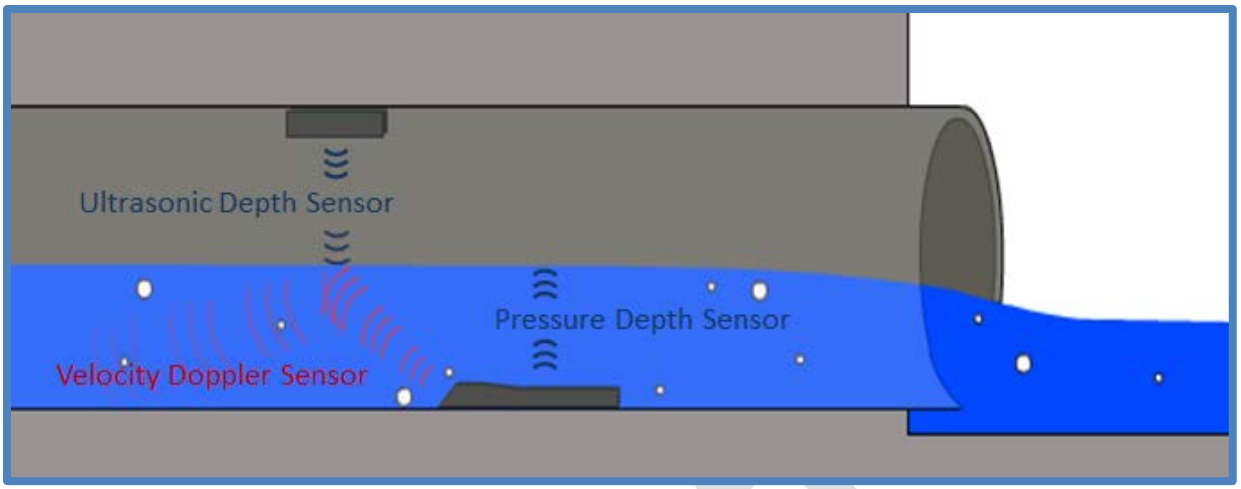
The most common types of flumes are the Parshall, Palmer-Bowlus, HS, H, and HL flumes, and the trapezoidal flume. As with weirs, the downstream side of the flume should be free flow conditions with no backwater conditions. The installation of a flume will require the same hydraulic calculation checks and requirements as outlined above in the weirs section. Additionally, a flume will also require a water level sensor to record level. Flume installation requirement calculations such as minimum approach length, maximum velocity and required slope will be necessary upon selection of the weir and installation placement. The manufacturer's installation guidelines will vary depending on the manufacturer, flume size, and flume type. The installation guidelines should be strictly followed in order to promote a laminar flow regime for accurately collecting level and flow data calculations.

There are numerous manufacturers of calibrated weir on the market. Some examples of these manufacturers include: Openchannelflow, CC Lynch, Global Water. Prices vary widely depending on the type and size of the weir but are typically around $1,000 to $7,000.

Area-Velocity Meters

Area-velocity meters are typically used at the connecting inlet and outlet piping directly servicing the GSI facility. For example, area-velocity meters are typically installed in locations such as: 1.) the overflow piping network that connects the GSI to the neighboring collection system, 2.) the neighboring collection system itself, and/or 3.) an inlet pipe from a stormwater outfall that discharges into a stormwater wetland or bioswale.

Area-velocity flow meters use sensors that monitor and record the mean velocity and depth. To measure mean velocity, the sensor uses continuous Doppler wave technology. The velocity sensor transmits a continuous ultrasonic wave, then measures the frequency shift of returned echoes reflected by air bubbles or particles in the flow to determine the velocity. Another sensor will measure the mean level to record depth. The level can be recorded either by using submerged pressure sensors that detect the height of water over the sensor, or by using unsubmerged ultra sonic wave depth measurements; both sensors are often used simulataneously to provided redunant backup capabilities. The recorded level and velocity by sensors within the open channel flow meter are then converted to a flow rate based on the equation Q (Flow) = (Flow Area based on Recorded Level and Channel Geometry) x (Recorded Velocity).



Depiction of the Sensor Measurements for Recording Velocity and Depth in an Open Channel Pipe Location

There are several manufacturers on the market that produce area-velocity flow meters for monitoring flow within GSI facilities and neighboring collection systems. Some of these manufacturers include: Hach/American Sigma, Teledyne Isco, and FloWav. Each manufacturer has strengths and weaknesses of their products depending on the hydraulic conditions of the collection system. The appropriate manufacturer and open channel flow meter should be selected based upon field investigations by an experienced and qualified expert. Typical costs for flow meters vary widely depending on the manufacturer and the sensor technology. Maintenance of the equipment is largely dependent upon site conditions where the area-velocity is installed. Installation locations with evidence of high surcharging, sedimentation and debris will require more frequent maintenance and cleaning of sensors. Typically recalibration of faulty sensors is performed by the manufacturer if measurements are shown to be erroneous.

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Typical Area-Velocity Meters Available from Hach/American Sigma

Data Logging and Communications Equipment

Data loggers are devices that detect signals from monitoring equipment (i.e. rain gage, level sensor, flow meter) and store the impulses that they generate at a user defined time increment. Most data loggers have multiple input ports and can accommodate several monitoring equipment devices. Generally there are two types of data loggers: internal data loggers and stand-alone data loggers.

Internal data loggers typically are provided as part of an all-in-one monitoring package system. Often, these “all inclusive monitoring systems” (data logger and monitoring equipment sensor(s) as one complete package) are adequate for GSI monitoring applications and can greatly simplify monitoring station setup and purchasing. However, a drawback to an all inclusive monitoring system is that often the data logger may only capable of reading sensors provided from the same vendor. Mixing and matching different monitoring equipment may not be possible with an internal data logger that is provided as part of an all-in-one package system.

Stand alone data loggers typically are just that, stand-alone. They are capable of receiving signals from mulitple types monitoring equipment from different manufacturers and stand alone from the monitoring equipment itself.

Before choosing a “monitoring system” over a stand-alone data logger, it is important to make sure that the programming options, data storage capacity, and sensor specifications (e.g., resolution, accuracy, design configuration, construction materials, power consumption) of the system are compatible with the proposed application and data needs. Quite simply, the selected data logger should be capable of recording and storing data from the selected monitoring equipment at the desired time increment.

Stand-alone data loggers suitable for stormwater monitoring applications are typically constructed of weather-resistant materials capable of protecting their internal circuitry from water and dust hazards. However, be aware that some common data loggers and auto-sampler heads do not function at subfreezing temperatures without retrofit. After-market heaters and thermostats can be purchased to enable year round continuous monitoring in cold climates. In addition, most models can be securely mounted in remote locations, providing protection from wind and rain, wildlife, and vandalism. A typical stand-alone data logger for field use generally consists of the following components: a weatherproof external housing or a “case”; a CPU or microprocessor; memory (RAM and/or Flash) for storing data and programs; data input ports; data output ports; one or more communications ports (remote access via cell, wireless broadband, land line, or radio frequency modem is available for some data loggers); and at least one power source.

Most stand-alone data loggers provide for user interface so that they can be field programmed and interrogated. The user interface can be a touch screen on the data logger or part of another device (laptop) connected to the communications port on the logger. Data stored may be retrieved by downloading directly to a laptop, extracting to a data transfer units, or downloading via remote access (wireless signal or telephone modem).

Systems that rely on volatile memory (i.e., RAM) for data storage require a backup power source such as a lithium battery to prevent data loss in the event the primary power fails.

Data loggers vary in size from 0.2 to 9 kilograms (0.5 to 20 pounds) or more. Both portable and fixed data logging systems with mounted weather resistant housing units are available. For long-term, unattended monitoring projects, a fixed data loggers capable of serving as a remote transmitting unit may be preferable to a portable one.

There are several manufacturers on the market that produce stand-alone data loggers. Some examples include Telog Instruments, Cambell Scientific, and Global Water. Prices for stand-alone data loggers widely vary depending on manufacturer and functionality (number of ports, power system, communications, housing unit, etc.). Often an additional charge will be required to obtain the software to program and interface with the data logger.

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3.4 Example GSI Monitoring Approaches

Bio-Infiltration and Rain Gardens

Bioswales

Infiltration Trenches and Tree Pits

Porous Surfaces

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3.5 3.5 Visual Inspection Monitoring Techniques for GSI

Section 3.5 provides general guidance for conducting routine visual inspection monitoring for GSI installations. Although visual assessment does not provide quantitative information on the performance of individual GSI in terms of water quality and quantity, it does provide a quick and inexpensive method to verify key conditions indicating whether the GSI facility is performing as designed.

More specifically, the objectives that visual assessment can potentially achieve are to:

- Prove the concept of GSI at a site level and at a block/neighborhood level;
- Understand how individual GSI functions hydraulically, which can infer ecological and chemical function based on the findings of the assessment;
- Evaluate how GSI performs locally in practice as a distributed strategy to impact primarily water quantity and quality, but also, by inference on the observed performance, the other associated benefits of GSI such as local flooding reduction and aiding economic development by increasing property values;
- A significant benefit of visual assessment is to advance and optimize GSI siting, design, construction, and maintenance and determine performance at installation and over time with a standardized visual assessment protocol using data that can be cataloged and referenced over time.
- Develop monitoring activities as education and outreach in that visual assessment can be performed by those other than technical stormwater professionals.

Water quality in the Chesapeake Bay region has been a driving force to develop many inspection and maintenance protocols for GSI. The Pittsburgh region can benefit from reviewing and adapting this information created from areas such as the Chesapeake Bay as appropriate. Regular inspections and maintenance of GSI are critical to ensure that pollutant removal performance is maintained over time so that they achieve the pollution reduction credits for compliance, as well as managing stormwater on site to reduce combined sewer overflows and improve stream quality. Much of the information in Section 3.5 is taken from Chesapeake Stormwater Network's Technical Bulletin No. 10 Version 2.0, October 20, 2013, *Bioretention Illustrated: A Visual Guide for Constructing, Inspecting, Maintaining and Verifying the Bioretention Practice*, henceforth noted as "CSN Technical Bulletin No. 10. For the full report, please visit the following link:

http://chesapeakestormwater.net/2013/04/technical-bulletin-no-10-bioretention-illustrated-a-visual-guide-for-constructing-inspecting-maintaining-and-verifying-the-bioretention-practice/

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Applying the principles outlined in the *CSN Technical Bulletin No. 1,* the following principles can be applied to visual inspection. A visual indicators approach for inspecting and maintaining GSI during routine maintenance, inspections and performance verifications can offer useful insight to how GSI BMPs are functioning when monitoring equipment is not readily available. The visual indicators approach is based on the following principles:

- Use simple visual indicators to conduct rapid inspections of individual practices in less than a half hour;
- Apply a "triage approach" to focus time and staff resources on fixing the practices in the worst condition;
- Use measurable and numeric maintenance "triggers" to develop a punch-list of maintenance tasks and let the GSI owner know how to fix minor, moderate and severe maintenance problems;
- Shift visual inspection responsibilities to inspectors, landscape contractors, and others who may not be trained engineers but could learn to do LID inspection. Confine the efforts of engineers to less frequent and in-depth “forensic” construction inspections to ensure they are installed and operating properly.

Establishing a proactive maintenance plan with consistent site visit will allow the maintainer to better understand how the installation is functioning, address minor issues quickly, schedule follow-ups for moderate issues and report to the facility owner, major issues that may need further investigation. Maximizing technologies such as mapping, photography, and data management will better integrate maintenance records for detailed tracking of facilities.

Key Parameters for Conducting Visual Inspections

PWSA is in the process of creating visual inspection checklist for the GSI BMPs commonly used in Western PA, but in the interim, referring to *CSN Technical Bulletin No. 10* can be a valuable resource. Each profile sheet describes the visual indicator, its purpose, pictures demonstrating the different grading categories, the maintenance triggers and the corresponding task or investigation needed to maintain or repair the facility.

Depending on the type of GSI, these key visual indicators include:

- Inlet obstruction or erosion;
- Whether pretreatment exists or is effective;
- Swale erosion;
- Flow distribution and surface dimensions;
- Side slope erosion;
- Ponding volume and depth of standing water;
- Presence of sinks holes;
- Sediment deposition;
- Mulch depth;
- Condition and maintenance of vegetation;
- Pavement edge integrity;
- Level spreaders;
- Check dams;
- Outlets, underdrains, overflows.

Recommended Equipment

Some equipment can help facilitate visual assessment, such as a camera, tape measure, soil auger, as-builts, etc. and is listed in Table 10 in Section 4 of *CSN Technical Bulletin No. 10.*

Process

Throughout the implementation process, visual inspection can be deployed as part of a standard maintenance plan that can be used during all stages of a GSI's lifecycle including:

- Construction Inspection
- Project Acceptance
- Field and Maintenance Inspections
- BMP Performance Verification
- Forensic BMP Investigations

The visual indicators approach allows for a rapid assessment of the bioretention in 10 to 30 minutes by following a prescribed sequence of items to look for. As the GSI facilities are assessed, each visual indicator is given a rating to better determine how the system is functioning and the necessary steps to optimize functionality.

Inspection or visual assessment may be considered the most basic level of green stormwater infrastructure monitoring. The following section offers guidelines to better assess the GSI facility at the key stages listed above.

Construction Inspection / Project Acceptance – The Initial Verification of BMP Installation

As new GSI facilities are designed and installed throughout the City of Pittsburgh, it is imperative that PWSA coordinate with the design team to ensure the installation can be included as a source reduction project with regulators as part of our Consent Order Requirements. PWSA can verify stormwater calculations based upon our internal criteria and offer design review for new source reduction projects happening within the City of Pittsburgh. Each installation is also be assigned a unique identifier for PWSA records.

The initial verification of performance is completed by either the lead designer or engineer or by the construction management inspector overseeing the installation. Construction inspection is an important step to take to ensure that the project is built to its design specifications, and any changes that are made in the field are acceptable.

Construction inspection is performed by an engineer or trained stormwater professional who inspects the installation at critical points in the construction process. This inspection will verify specified materials and installation protocols are adhered and note any changes to the design based on field conditions.

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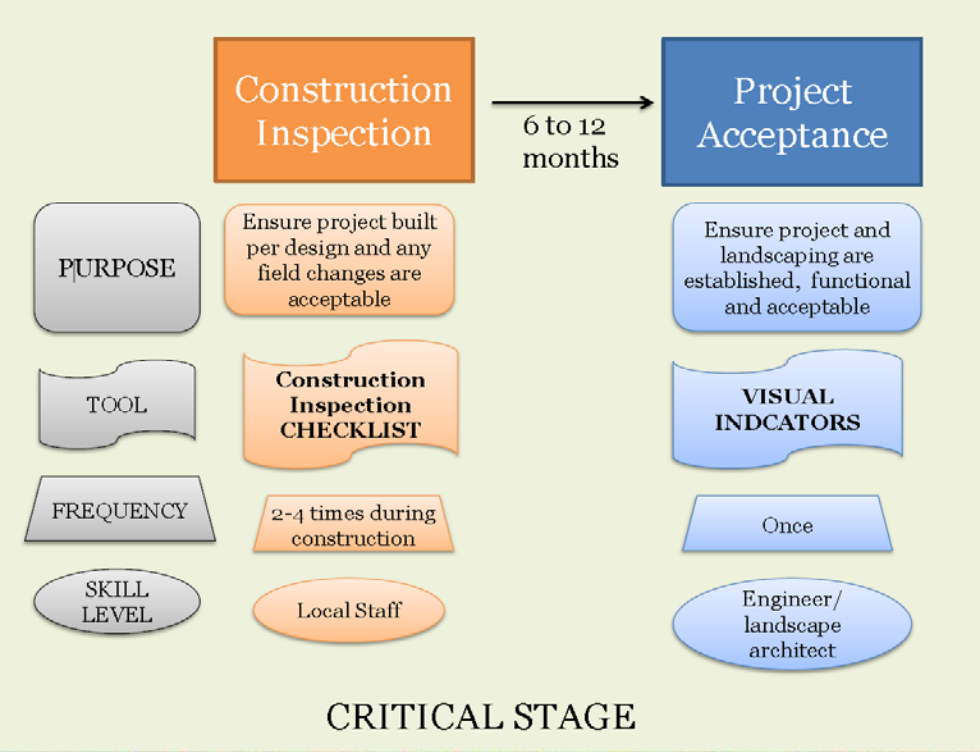
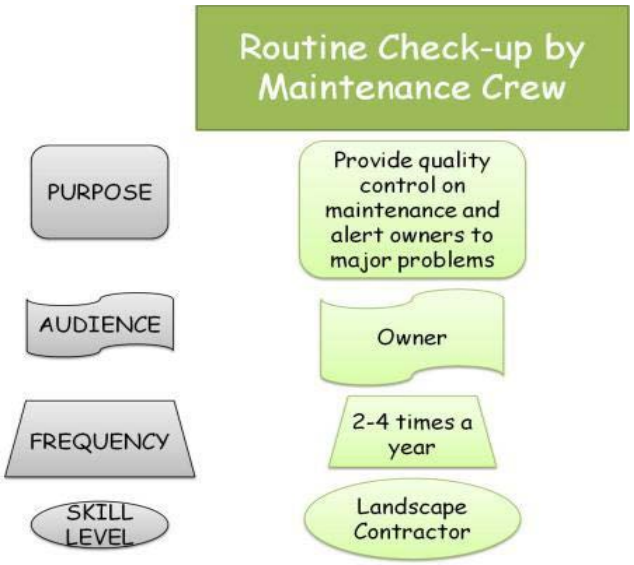


From Chesapeake Bay Stormwater Training Partnership Webcast, " Trust but Verify ! Getting Ready for the New Era of Urban BMP Verification in the Chesapeake Bay " December 4, 2014.

See Table 8 in Section 2 of *CSN Technical Bulletin No. 10* for the steps of a construction sequence for bioretention, and a list of the critical inspection points in the sequence, such as confirming that inflow actually captures runoff.

Regular Maintenance and Field Inspections

Routine maintenance checkups occur 2-4 times a year as part of a regularly scheduled maintenance visit and are necessary in order to provide quality control on maintenance activities and/or to alert owners of any major problems that may be developing. The purpose of a routine maintenance checkup is to "catch" minor problems before they turn into more serious problems.



Field inspections indicates whether a BMP is performing as originally designed and if corrective actions are needed to optimize its effectiveness in addressing CSO reduction and water quality perimeters. Performance verification uses a subset of the list of visual indicators that assess the hydrologic function and pollutant removal capability of GSI installations, by answering three simple questions:

1. Does it still physically exist? i.e., can you find it and are the conditions and cover in the contributing drainage area still the same?

2. Is it still operating to treat and reduce runoff as it was originally designed?

3. Is the maintenance condition sufficient to still support its pollutant reduction functions?

Table 12. Key Visual Indicators for Performance Verification

Hydrologic Condition	Severe Bed Sinking	Runoff moves too quickly through the bioretention
	Severe Inlet Obstruction	Runoff is not able to get into the bioretention
	Standing Water	Runoff is not fully being treated
	Loss of Surface Ponding Capacity	Runoff is not fully being treated
	Severe Erosion at Outlet	Runoff is bypassing the bioretention
Maintenance Condition	Inadequate Vegetative Cover	Runoff is not fully being treated
	Severe Pretreatment Failure	Reduced longevity of the bioretention
	Severe Inlet or Side Slope Erosion	Sediment delivery to filter bed

Visual Indicators

The visual indicators approach allows for a rapid assessment of GSI facilities within 10 to 30 minutes by following a prescribed sequence of items to look for. Each of these 'visual indicators' is assessed based on a set of numeric triggers and assigned a grade of Pass, Minor, Moderate or Severe. The templates and profile sheets for these assessments are described below. This assessment results in a punch-list of maintenance tasks to be conducted on the GSI facility in the case of a 'severe' rating, requires an in-depth intervention. This approach limits the use of expensive engineer time for the inspections where they are really needed. The intent is limit inspection time, review good facilities quickly which allows for more time to be spent on problematic facilities. An analysis of a Bioretention Area will be used to more fully explain how the visual indicator process should function.

Below is a checklist for a Bio-Retention Facility.

Table 9. Visual Indicators for a Bioretention Practice

No.	INDICATOR	Construct	Accept	Maintain	Verify	FBI
1	Inlet Obstruction		X	X	X	X
2	Erosion at Inlet		X	X		X
3	Pretreatment	X	X	X		X
4	Structural Integrity, Safety Features		X	X		X
5	Surface Area	X	X	X		
6	Side slope Erosion		X	X		X
7	Ponding Volume	X	X	X	X	X
8	Bed Sinking		X	X	X	X
9	Sediment Caking		X	X	X	X
10	Standing Water		X	X	X	
11	Ponding Depth	X	X	X	X	X
12	Mulch Depth/Condition	X	X	X	X	
13	Trash			X		
14	Bed Erosion		X	X		
15	Vegetative Cover	X	X	X	X	X
16	Vegetative Condition		X	X		X
17	Vegetative Maintenance		X	X		
18	Outlets, Underdrains, Overflows	X	X	X	X	X

Applying the visual indicators during an inspection is best done in a prescribed sequence to systematically evaluate the GSI facility. Each of the indicators has been assigned to a "zone" or area within the facility that corresponds with the sequence an inspector would follow during the assessment of a Bioretention facility:

- Inlet zone
- Side slope zone

- Bed zone
- Vegetation zone
- Outlet zone

Although each of the indicators should be assessed during an inspection, often an inspector will be able to immediately see any key trouble spots occurring within the facility. These primary or key indicators can inform the inspector instantly whether the facility is operating on a most basic level. Once these key indicators have been reviewed the inspection can proceed to assess the remaining indicators.

The key indicators for a bioretention area are:

- Erosion within the bioretention
- Standing water anywhere in the basin
- Sediment or debris blocking inlets or outlets and causing
- Lack of or inappropriate vegetation

By assessing the individual components of the facility in this manner, it is possible to comprehensively yet rapidly evaluate the functionality of the entire bioretention area. If a facility is not functioning as needed from a compliance standard, a more in-depth investigation may be needed by a stormwater professional. This professional will identify and recommend the improvements necessary to address the maintenance problems identified in the site visit.

In-Depth Investigation

An In-depth analysis will diagnose why a practice is failing or has failed, and then come up with a plan to bring it back into compliance. These specialized assessments require a skilled stormwater professional to find and fix any severe maintenance problems discovered at the GSI facility. Below is an example provided by the XX report for a bioretention area.

Table 13. Key Visual Indicators that Trigger an FBI for Bioretention

No.	INDICATOR	Status
1	Severe Inlet Obstruction	Most runoff cannot enter the facility
3	Inadequate or Lack of Pretreatment	Severe accumulation of sediment in facility
4	Structural Integrity	Facility or adjacent infrastructure at risk of failure
2, 6, 14	Severe Inlet Erosion, Sideslope or Bed	A foot or more of gully erosion
5, 7, 11	Severe Design Departures	More than 25% departure from design assumptions for surface area, ponding depth and/or contributing drainage area
8	Severe Bed Sinking	A foot or more of localized bed sinking and/or sediments observed in underdrain
9	Severe Sediment Caking	More than two inches of deposition in the facility
10	Severe Standing Water	More than 3 inches of ponding 72 hours after rain
15	Severe Vegetative Cover	35% or less vegetative cover

Incorporation of Technology

Successful visual inspection is useful during rain events but time constraints may prevent inspector from getting to each GSI facility to see how they perform in action. Newer technologies such as cameras and time lapse photography can be installed to track performance and how key features are functioning such as; are the inlets and their placement maximizing capture, is more sediment entering the system than expected and how long is the ponded water infiltrating at. This information can be analyzed and offer design revisions for current underperforming installations while establishing new design criteria for future designs.

Conclusion

Visual inspection is an effective tool that can be incorporated into all monitoring plans. This section outlined key parameters on how to conduct visual inspections for a common BMPs in the Pittsburgh region. As the Authority continues to develop its monitoring protocols this section will be refined but there are multiple references available to assist in developing a visual inspection plan.

References

Chesapeake Bay Stormwater Training Partnership Webcast, "Trust but Verify! Getting Ready for the New Era of Urban BMP Verification in the Chesapeake Bay," December 4, 2014.

CSN TECHNICAL BULLETIN No. 10 Version 2.0 October 20, 2013. "Bioretention Illustrated: A Visual Guide for Constructing, Inspecting, Maintaining and Verifying the Bioretention Practice."

Instructional Videos

The Chesapeake Stormwater Network has a 3-part instructional video series on Low Impact Development construction, installation and maintenance. These videos were produced by the Center for Watershed Protection under contract with the Chesapeake Stormwater Network with funding from the National Fish and Wildlife Foundation with additional support from Walmart and the Keith Campbell Foundation.

The first video, A Guide to Proper Construction Techniques for contractors, local governments and involved homeowners, covers sound construction practices and the importance of following the construction sequence to ensure that the LID practice functions as designed and was designed for people who are looking for information on how to properly install a BMP such as contractors, local governments and involved homeowners.

The second video, Inspecting LID Stormwater Practices: A Guide to Proper LID Inspection Practices for local governments and contractors, offers tips on how to conduct routine and more formal inspections of LID-type stormwater management practices such as bioretention, bioswales, and permeable pavement and was designed for individuals looking for information on how to properly inspect stormwater practices such as local government inspectors and contractors.

http://chesapeakestormwater.net/training-library/design-adaptations/stormwater-bmp-maintenance/

3.6 Simulated Rainfall Performance Test GSI Monitoring

Overview:

Simulated runoff testing is an assessment tool used to observe how the stormwater BMP performs in a predetermined design storm while measuring infiltration, treatment, and storage are taken. Simulated Runoff Tests can be used to determine volume reduction, peak flow reduction, and pollutant removal efficiency. These tests are a useful way to properly site GI BMPs, validate modeling assumptions, identify maintenance or functionality issues early so designs can be adjusted prior to construction. As the Pittsburgh Water and Sewer Authority establish their Green Infrastructure Program, it is imperative to establish monitoring protocol that will demonstrate how various BMPs function to better inform design and construction as well as long-term operations and maintenance. As different monitoring protocols and techniques are being trialed at this time, simulated runoff testing will be an effective way to provide hydrologic data that will help PWSA demonstrate the feasibility of green infrastructure as part of our Consent Agreements.

Advantages

- Experiments are highly controlled, focusing on specific goals
- More accurate, with fewer tests required for statistical significance
- No equipment left in the field

Disadvantages

- Cannot be performed without an adequate water supply
- Requires substantial equipment and operational knowledge
- Somewhat limited in scope, depending on complexity of experiment

Parameters:

Simulated Runoff Testing requires more effort and cost than visual inspections and capacity testing, but significantly less than extensive performance monitoring. Testing time can vary from days to several weeks. For the intents and purpose for PWSA, simulated runoff testing allow for the Authority to test different hypotheses, benchmark actual performance under a variety of runoff scenarios and compare/contrast different green infrastructure systems against one another. It therefore provides very flexible set of performance monitoring and evaluation tools for green infrastructure.

Collecting this data will quantify the benefit of the facilities, improve overall design and function, and lower maintenance costs. Flow testing provides a relatively inexpensive and accurate method to gather this data for various design storms. Using a fire hydrant and a very accurate flow meter, almost any storm event can be simulated with regards to flow rates and volumes. In combination with accurate outflow monitoring and field observations, reliable performance data can be compiled in a relatively short period of time.

Equipment:

Equipment is organized in three separate lists. Sensitive electronic equipment and field forms should be stored in the vehicle away from hand tools.

1. “Clean Bag”
- Laptop with appropriate software loaded

- Appropriate interrogation connection cable
- Clipboard and pencils
- Field forms and permits
- Digital camera

2.) “Tool Bag”
- Tape measure
- Flashlight
- Hooks needed to remove grates for access
- Hammer
- Small pry bar or chisel
- 2 flathead screwdrivers
- Work gloves
- Safety goggles
- Safety Vest or High Visibility Shirt
- Hardhat and Steel toe Boots if the site is an active construction site
- Traffic Cones
- Hose Ramps
- Green Street Hydrant Testing Sign
- Shop rags
- Hand sanitizer
- First Aid Kit
- Hydrant Wrench, CCL Key, and or a Hydra Shield - Depending on hydrant type to be used
- Sand bags to control flow near green inlet
- Work platforms
- A/V Sensor with 15” mounting ring and connecting cable for Logger

3. "Hydrant Testing Apparatuses”
- Associated Pipe fittings (TBD)
- "2 1/2" inch Diameter x 100' Long Fire Hose - (Can vary from site to site based on nearest hydrant available, available from PWSA).
- Portable Meter Test Equipment - Sensus W-1250 or equivalent
- Swivel Diffuser and associated pipe fittings to be attached to flow meter outflow.

Process:

Currently, PWSA will adopt the operating procedures detailed in the Philadelphia Water Department Comprehensive Monitoring Plan, “*Appendix D: The Water Department’s Standard Operating Procedures for Simulated Runoff Testing of Green Stormwater Infrastructure Practices”.* The following is a general outline of the PWD operating procedure for simulated runoff testing for green infrastructure:

Office Procedures Prior to Field Simulation:

Step by Step Process

The following is a general outline of the BH proposed operating procedure for field trial testing for the following monitoring devices on the Rosedale Project.

Office Procedures Prior to Field Simulation:

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1. Check batteries of laptop and clocks, verify SD storage card is in the camera and has necessary storage.
2. Use current Fire Hydrant operating form, available from PWSA
3. Prepare field forms by entering the following information.
   a. Project name:
   b. Project location:
   c. Determine PWSA ID for each catch basin to be visited.
   d. Enter the monitoring device ID(s) and sensors installed.
   e. PWSA contact name and local contact name if present in the database
   f. Interrogate nearby rain gage and determine if there has been significant (> 0.05 in) rainfall within the past 24hrs and document.
4. Print maps/directions if necessary.
5. Determine target flows and volume to be applied.
6. Verify that water meters to be used in procedure will accommodate the target flows.
7. Prepare water level logger by verifying functionality
8. Review Hydrant Operating Procedure and contact appropriate PWSA operations personnel if you have not received training to safely operate Fire Hydrants.
9. Verify that hydrant can produce necessary flows to replicate design storm through review of hydrant fire flow test records. Field verify the pressure and corresponding flow rate(s) required for testing at the hydrant.
10. Verify that the tools for operating the closest hydrant to the site in question are correct and current.
11. Post no parking signs the day before or day of, if required.
12. Make sure each participant is familiar with the procedure and knows the specific tasks they will be responsible for.
    a. Operation of the hydrant meter: PWSA
    b. Taking manual readings at water meter, and keeping master time record:
    c. Take visual level readings using the staff gage, interrogation of A/V and level logger channels:
    d. Photo documentation of site, Interacting with public, and ensuring safe operation of all equipment:

Note: If any of the following conditions are true the field trials testing cannot be administered:
1. Unsafe field conditions as determined by personnel administering the performance testing.
2. Presence of excessive sediment/debris in the area of flow application that cannot be removed.
3. Any other arbitrary or unconsidered condition that may occur and be deemed unsafe or considered to significantly impact the results of the test.

Field Simulation Procedures

1. Where able, video document the procedure.
2. Sketch testing layout showing equipment locations and arrangements, inlet points, and measurement points. Note where cars could or do impede the administration of the test.
3. Inspect the site for any unusual conditions and establish appropriate safety measures such as cones or pedestrian barriers.
4. Document initial test conditions via photos, making sure to take pictures of inlets, inside inlets, monitoring device locations, and hydrant location noting conditions on the field reporting form.
5. Access the monitoring location remove and/or retrieve stench hood. Use a flashlight to inspect, or sound the bottom of the catch basin if possible to determine if there is debris accumulation.

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6. Take a manual water level reading before beginning any flow testing, Record the water level, time, units, and measurement device (e.g., staff gage) on field form where indicated.
7. Physically connect to logger, verify device ID and observe level data. Compare to manual reading on staff gage.
8. Install A/V probe on mounting ring in outlet pipe.
9. Wipe the logger clean and inspect the A/V sensor port for any debris. Carefully clean the port with a bottle brush or pipe cleaner if necessary. Connect A/V probe to logger via cable.
10. Verify both sensors are recording at the same time interval. e.g. Both sensors recorded a data point for the time 12:00:00 AM, not one at 12:00:00 and the other at 12:01:30.
11. Use PWSA Hydrant Operating Procedure form to begin operation of nearby Hydrant.
12. Once Hydrant is ready, install hydrant meter, other testing apparatus and associated hose and hose fittings.
13. Place Sensus WL 1250 portable water meter with diffuser at either of the following two points as field conditions allow.
    a) At an inflow point such that the discharge from the meter will reach the inlet at approximately steady state (slightly upstream of inlet to allow turbulence to dissipate a specific distance for different flows TBD.)
    b) Remove inlet grate and direct the diffuser so that water will discharge directly into the inlet.
14. If sand bags are used to minimize bypass ensure that they are safely arranged at the inlet.
15. Photo Document setup prior to and after applying flow to the system.
16. Apply flow to the system noting the start time in the field report.
17. Fill catch basin to just above outlet pipe invert to create a discharge, and allow level to stabilize in catch basin to where there is no discharge. Note this level on staff gage and enter on the field trials form.
18. Replace stench hood.
19. Using the hydrant meter-begin the test.

Note: For the purposes of this draft, the primary device during the testing is the hydrant meter with the installed A/V probe to be used as backup. This will depend on the precision and accuracy achievable by the hydrant meter supplied by PWSA.

Procedure 1: Target Flow Approach

1. The hydrant flow meter will be set to deliver flow to the catch basin at the first target flow rate.

Proposed Target Flows (gpm)
50
100
250
500
750
1000
1500
2000

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2500

3000

2. The level in the catch basin will be observed and allowed to stabilize for 5 minutes holding the flow rate constant. At that point, the level in the catch basin will be observed and the staff gage reading recorded.
3. Flow delivery will then be increased to next target flow rate, allow to stabilize for 5 minutes and the level in the basin will be recorded.
4. The procedure is repeated in stepwise manner for each target flow value with each associated steady state level recorded.
5. After the final flow target has been done, the flow delivery will be turned off and the level allowed decrease to the starting zero discharge level. The time to achieve no discharge will be tracked and entered.
6. Record the monitoring device IDs, water level, time, units, and A/V channel data readings on field form.

Reference Materials:

City of Portland, Bureau of Environmental Services, Portland, Oregon
https://www.portlandoregon.gov/bes/article/63096

St. Anthony's Fall Laboratory, University of Minnesota
http://stormwater.safl.umn.edu/sites/stormwater.safl.umn.edu/files/102406erickson.pdf

Philadelphia Water Department, Philadelphia, Pennsylvania
http://phillywatersheds.org/ltcpu/GCCW%20Comprehensive%20Monitoring%20Plan%20Appendices.pdf

Southern California Coastal Water Research Project, Westminster, California
ftp://ftp.sccwrp.org/pub/download/DOCUMENTS/TechnicalReports/343_characteristics_of_parkinglot_runoff.pdf

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Sample photos but we will have new ones Fall 2015 as we refine this approach and conduct a field simulation with the Rosedale Runoff Reduction Project.

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Section 4.0 – GSI Pollutant Removal Performance Monitoring

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4.1 Importance of Determining GSI Pollutant Removal Performance

Uncontrolled stormwater runoff, particularly within urban settings, has been shown to be a significant contributor of pollutant loadings to receiving water bodies. According to the EPA, urban stormwater is listed as the "primary" source of impairment for 13 percent of all rivers, 18 percent of all lakes, and 32 percent of all estuaries (EPA. 2000. National Water Quality Inventory. 305(b) List Report). Findings such as these have led to an increased focus by regulatory agencies for controlling stormwater runoff from urban stormwater runoff. The use of GSI has been widely adopted by the EPA and other regulatory agencies throughout the United States as a viable solution for filtering and removing pollutants originating from urban sources.

The true effectiveness of GSI facilities to filter and remove stormwater runoff pollutants is dependent upon many factors including but not limited to: the type of GSI facility and specific design components, land use and topography of the GSI contributing drainage area, local geology, and regional climatic rainfall event characteristics (antecedent dry time, rainfall intensity, rainfall duration, etc.). Other than the type of GSI facility and specific design components, the factors previously listed vary depending on spatial location. While extensive research has been performed on the pollutant removal effectiveness of GSI elsewhere in the United States, very little has been performed within the Pittsburgh region. It is important to determine if spatial factors have an influence on the effectiveness of GSI for removing pollutants in the Pittsburgh region. The results gleaned from these studies will confirm the effectiveness of GSI for achieving pollutant reduction goals and meeting water quality regulatory requirements.

In general, GSI water quality monitoring programs are typically developed to obtain information to help answer one or more of the following questions:

- What pollutants are most prevalent and detrimental to the receiving water quality for various types of urban land uses?
- What degree of pollution control or effluent quality does a given GSI facility provide on a typical annual basis?
- How does the GSI facility performance vary from pollutant to pollutant?
- How does the GSI facility performance vary during discrete storm events with varying rainfall depths and intensities?
- How do specific design components such as pre-treatment areas and engineered soil media affect pollutant removal performance?
- How does the GSI performance vary with different operational and/or maintenance approaches?
- Does the GSI performance vary over time and season to season?
- How does the GSI performance vary for each type of GSI technology?

The ability answer these questions is a vital planning stage component prior to developing a meaningful GSI water quality monitoring program.

Section 4.0 of the manual draws heavily upon the following two existing documents. For more in-depth information on water quality monitoring procedures and the current state of urban stormwater, the reader refer to the EPA 2002 and NRC 2008 reports.

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- EPA, 2002. Urban Stormwater BMP Performance Monitoring – A Guidance Manual for Meeting National Stormwater BMP Database Requirements. Washington, DC: EPA Office of Water
- NRC, 2008. Urban Stormwater in the United States. Washington, DC.

Sources:
EPA. 2000. National Water Quality Inventory. 305(b) List. Washington, DC: EPA Office of Water.

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4.2 Pollutants of Concern in Urban Stormwater Runoff

This section details stormwater runoff characteristics for urbanized land uses typically seen in the developed areas of the greater Pittsburgh region. Stormwater runoff pollutants from land uses such as agriculture, livestock farming, and general rural /undeveloped settings are not covered within this section.

In urbanized settings, the sources of stormwater runoff pollutants are generally broken into three categories:

- pollutants from urban construction and land disturbance activities,
- pollutants from existing industrial areas, and
- pollutants from existing and largely "stabilized" urban areas (municipal stormwater).

The management of stormwater runoff from urban construction and land disturbance activities are primarily handled through construction permitting processes by local, state, and county regulatory agencies through erosion and sedimentation pollution prevention plans. Industrial stormwater runoff is typically site dependent based on the nature of the industrial activity and the potential pollutants used in the industrial processes; stormwater runoff management plans and GSI strategies from industrial sites should be considered on a site-by-site basis.

This section provides an overview of pollutants from existing and stabilized urban area (municipal stormwater runoff.) The current understanding of the characteristics of stormwater runoff pollutants from municipal stormwater runoff are primarily understood through efforts of the National Stormwater Quality Database (NSQD). Since 2001, the NSQD has been compiling data from EPA's National Pollutant Discharge Elimination System (NPDES) stormwater permit program for larger Phase 1 municipal separate storm sewer system (MS4) communities. As a condition of Phase I permits, municipalities are required to establish a monitoring program to characterize their local stormwater quality for their most important land uses discharging to the MS4. Although only a few samples from a few locations were required to be monitored each year in each MS4 community, the many years of sampling and large number of communities has produced a database containing runoff quality information for nearly 10,000 individual storm events over a wide range of urban land uses from over 100 MS4 communities. The NSQD makes it possible to statistically compare runoff from different municipal stormwater land uses for different areas of the country. The NSQD contains stormwater runoff water quality data from about one-fourth of the total number of communities that participated in the Phase I NPDES stormwater permit monitoring activities. The database is located at http://www.bmpdatabase.org/nsqd.html.

The NSQD in 2015 released version 4.0 of the database. As of the authoring of this document the 10,000 individual results of the database had not yet been compiled and summarized for easy public dissemination. The results presented below are taken from version 3.0 of the data base released in 2008. These results are taken directly from the National Research Council's (NRC) 2008 report "Urban Stormwater in the United States".

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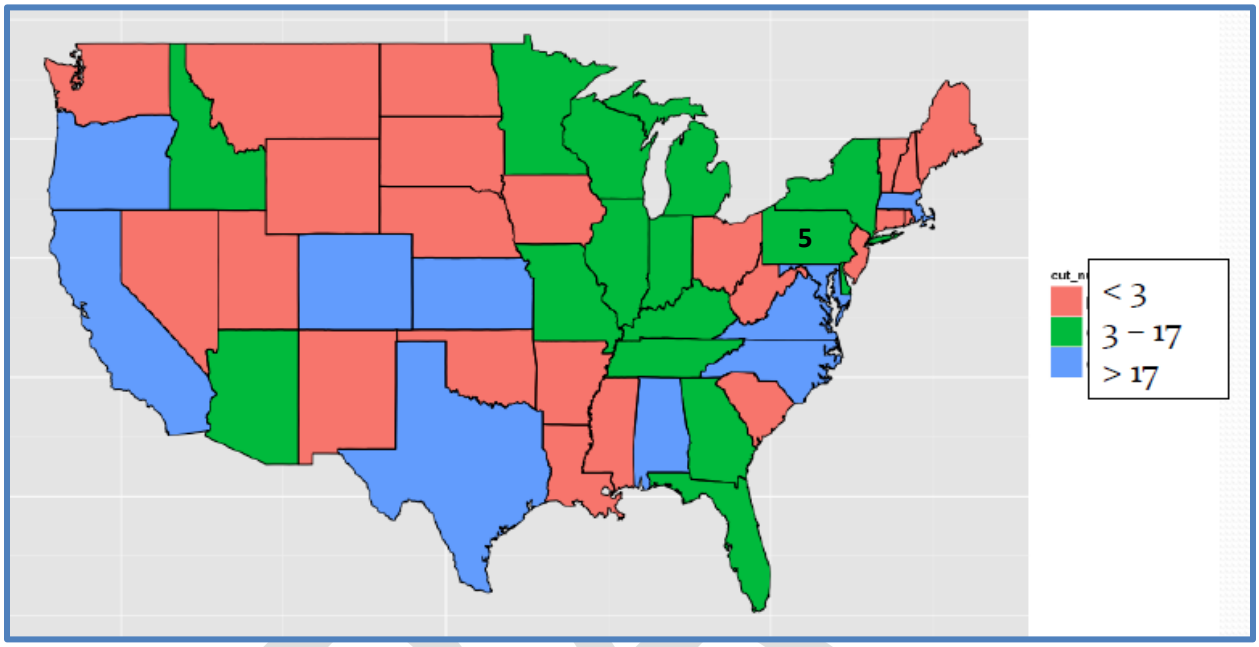
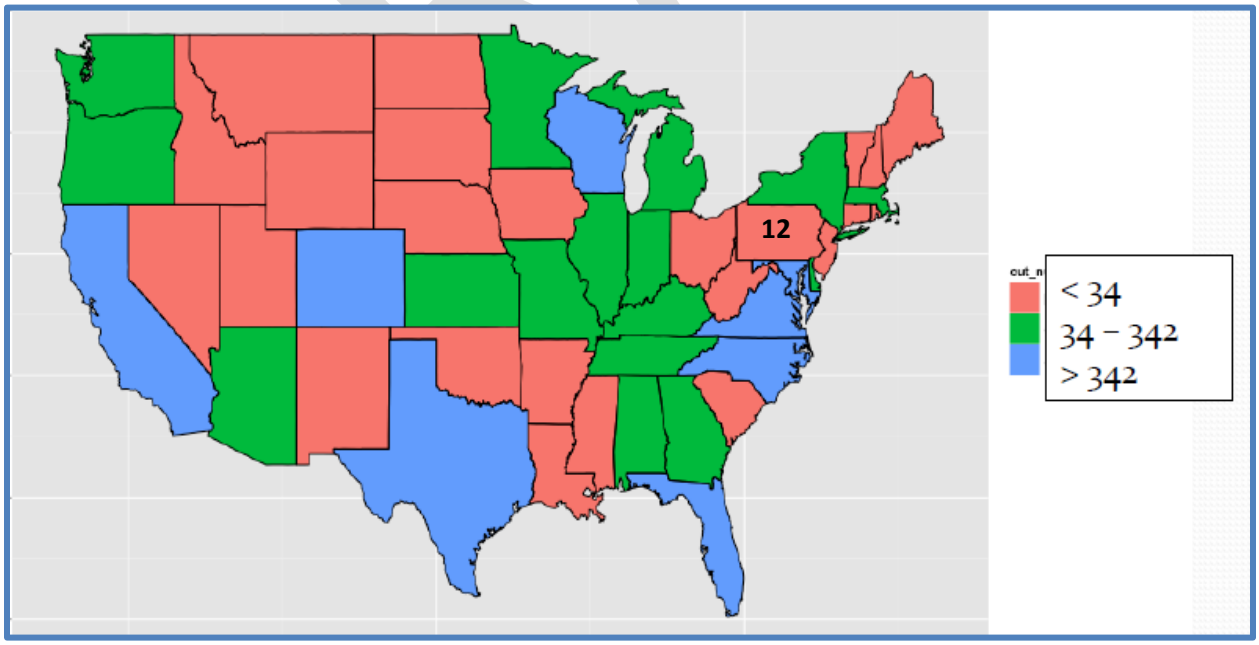
Summary of Selected Urban Stormwater Runoff Water Quality Data in NSQD version 3.0

	TSS (mg/L)	COD (mg/L)	Fecal Colif. (mpn/100 mL)	Nitrogen, Total Kjeldahl (mg/L)	Phosphorus, Total (mg/L)	Cu, Total (ug/L)	Pb, Total (ug/L)	Zn, Total (ug/L)
All Residential Areas Combined - All Regions of United States								
Coefficient of Variation (COV)	2.0	1.0	5.7	1.2	1.6	1.9	2.1	3.3
Median	59.0	50.0	4200	1.2	0.3	12.0	6.0	70.0
Number of Samples	2167	1473	505	2026	2286	1640	1279	1912
% Samples Above Detection	99	99	89	98	98	88	77	97
All Commercial Areas Combined - All Regions of United States								
Coefficient of Variation (COV)	1.7	1.3	6.1	1.1	1.4	2.1	2.0	1.7
Median	73.0	59.0	2850	1.4	0.2	19.0	20.0	156.2
Number of Samples	594	474	317	560	605	536	550	596
% Samples Above Detection	98	98	94	97	95	86	76	99
All Freeway Areas Combined - All Regions of United States								
Coefficient of Variation (COV)	2.6	1.0	2.7	1.2	5.2	2.2	1.1	1.4
Median	53.0	64.0	2000	1.7	0.3	17.8	49.0	100.0
Number of Samples	360	439	67	430	585	340	355	587
% Samples Above Detection	100	100	100	99	99	99	99	99
All Institutional Areas Combined - All Regions of United States								
Coefficient of Variation (COV)	1.1	1.0	0.4	0.6	0.9	0.6	1.0	0.9
Median	18.0	37.5	3400	1.1	0.2	21.5	8.6	198.0
Number of Samples	23	22	3	22	23	21	21	22
% Samples Above Detection	96	91	100	91	96	57	86	100
All Open Space Areas Combined - All Regions of United States								
Coefficient of Variation (COV)	1.8	0.6	1.2	1.2	1.5	0.4	0.9	0.8
Median	10.5	21.3	2300	0.4	0.0	9.0	48.0	57.0
Number of Samples	72	12	7	50	77	15	10	16
% Samples Above Detection	97	83	100	96	97	47	20	20

While the table above provides a quick snapshot of the characteristics of municipal stormwater for various land uses across the United States, it is also important to note that there is a lack of data in the NSQD for Pennsylvania and the Pittsburgh Region. Below are maps provided by the University of Alabama that show the geographic breakdown of the data within the NSQD version 4.0. Within the NSQD there are only five pollutant monitoring locations (all in Philadelphia) and 12 pollutant monitoring events originating from Pennsylvania.



Number of Monitoring Locations by State in the NSQD version 4.0 (5 in Pennsylvania)



Number of Total Sampling Events by State in the NSQD version 4.0 (12 in Pennsylvania)

The previously mentioned NRC report “Urban Stormwater in the United States” also notes that in terms of regional differences, significantly higher concentrations of TSS, BOD5, COD, total phosphorus, total copper, and total zinc were observed in arid and semi-arid regions compared to more humid regions. In contrast, fecal coliforms and total dissolved solids were found to be higher in the upper Midwest. The 2008 NRC report also describes other urban factors which are known to have an influence on the quality of stormwater runoff from municipal stormwater. These factors include:

- Effects of roofing materials particularly galvanized or rusted metal sheeting,
- The use of different types of pavements for resurfacing particularly asphalt and tar coats,
- Effects from pavement maintenance and street sweeping activities,
- The contribution and seasonal variability of dry weather groundwater discharges from MS4s,
- Variations due to winter maintenance activities and snowmelt, and
- Effects from atmospheric deposition based on regional air quality.

As shown in this section there are many factors which can have effect on the type of pollutants that are present in municipal urban stormwater runoff. These factors should be considered when conducting water quality studies to determine the pollutant removal effectiveness of GSI within the Pittsburgh region.

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4.3 Water Quality Monitoring and Procedures

In general, water quality monitoring programs in GSI facilities are largely dependent upon the following factors:

1. The selected water quality pollutants for laboratory analysis,
2. The number of samples collected for laboratory analysis during each storm event,
3. The total desired number of storm events for collecting samples, and
4. The in-house available staff and technical expertise.

Each of these factors will primarily determine the complexity, scope and cost for conducting a GSI water quality monitoring program.

The principal challenge for implementing water quality monitoring programs is the temporal and spatial variability of stormwater runoff pollutant concentrations. Stormwater quality at a given location can oftentimes vary greatly both between storms and during a single storm event, and thus a small number of samples are not likely to provide a reliable indication of stormwater quality at a given site or the effect of a given GSI facility. Therefore, collection of numerous samples is generally needed in order to accurately characterize stormwater runoff quality at a site and the associated GSI facility removal effectiveness. Before one begins a water quality monitoring program, it is critical to clearly identify and prioritize the scope and goals of the program.

Once the scope and goals are defined, the Standard Operating Procedures (SOPs) must be developed and the staff adequately trained. The quality of the water quality data produced is directly related to the methods employed and the training of the field staff. A vital part of any water quality monitoring program should be an extensive training program that involves the complete familiarization with the GSI facility(s) and the water quality sampling methods being performed. SOPs should be developed for each individual GSI facility being studied under the water quality monitoring program. GSI water quality monitoring SOPs at minimum should take into account:

1. The physical design and layout of the GSI facility to properly select the water quality sampling locations (where to sample),
2. The selected water quality pollutants for laboratory analysis (what to analyze),
3. The equipment and associated sampling procedures (how to sample),
4. The minimum and maximum sampling storm size criteria (when to sample),
5. Any field health and safety precautions associated with the GSI facility and water quality monitoring program.

The manner in which samples are collected and handled is critical for obtaining valid data. Each GSI facility is different depending on its physical layout and the SOP developed should take into account these design considerations. Additionally, each water quality pollutant is different in terms of proper handling, preservation, and storage techniques. SOPs developed should take into consideration the handling requirements of each pollutant.

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The following sections provide a general overview of common techniques and procedures for collecting water quality samples within GSI facilities. Sections include: collecting surface water samples using grab sampling and automated sampling techniques; collecting surface water quality data using continuous multi-parameter water quality monitoring sondes; and collecting subsurface groundwater water quality sampling using lysimeters.

Surface Water Grab Sampling Techniques and Equipment

One of the most common methods for collecting water quality samples within GSI facilities is through the use of manual hand grab sampling techniques. The term “grab sample” refers to an individual sample collected within a short period of time at a particular location. Analysis of a grab sample provides a "snapshot" of stormwater quality at a single point in time. Grab samples are suitable for virtually all of the typical stormwater quality parameters. In fact, grab samples are sometimes the only option for monitoring water quality pollutants that transform rapidly such as oil and grease, hydrocarbons, and bacteria.

In general, hand grab sampling techniques include collecting a sample at three locations within a GSI facility:

1. The upstream inlet of the GSI facility prior to any treatment,
2. Intermediate location within the interior of GSI facility itself such as the storage bowl area in a rain garden,
3. The outlet of the GSI facility (such as an overflow structure or an underdrain pipe)

The intent of collecting grab samples at each of these locations is to observe the relative change in pollutant concentrations as the pollutants travel through the GSI facility. To quantify pollutant reduction performance of the GSI facility, it is recommended to at minimum collect samples at both the inlet and outlet of the GSI facility.

The primary disadvantage from grab sampling methods is that they are generally not sufficient to develop reliable estimates of the event mean pollutant concentration or pollutant load because stormwater quality tends to vary dramatically during a storm event. Nevertheless, grab sampling has an important role in many stormwater monitoring programs for the following reasons:

- A single grab sample collected during the first part of a storm can be used to characterize pollutants associated with the "first flush." The first part of a storm often contains the highest pollutant concentrations in a storm runoff event, especially in small catchment areas with mostly impervious surfaces, and in storms with relatively constant rainfall. Thus, the results from single grab samples collected during the initial part of storm runoff may be useful for screening-level programs designed to determine which pollutants, if any, are present at levels of concern.

- Some measurable parameters, such as temperature, pH, total residual chlorine, phenols, volatile organic compounds (VOCs), and bacteria transform or degrade so rapidly that automated composite sampling can introduce considerable bias. (Note: Grab sampling is the typical method for VOCs because VOCs can be lost through evaporation

if samples are exposed to air during compositing. However, some automated samplers can be configured to collect samples for VOC analysis with minimal losses due to volatilization).

- Some pollutants, such as oil and grease and TPH, tend to adhere to sample container surfaces so that transfer between sampling containers must be minimized (if program objectives require characterization of the average oil and grease concentration over the duration of a storm, obtain this information from a series of grabs analyzed individually).

Manual grab sampling techniques and equipment typically consist of pre-conditioned laboratory sample bottles made of various types of materials. If site conditions allow, a grab sample can be collected by holding the laboratory sample bottle directly under the lip of an outfall or by submerging the bottle in the flow. A pole or rope may be used as an extension device if field personnel cannot safely or conveniently approach the sampling point. Alternatively, a clean, high-density polyethylene bucket may be used as a bailer and sample bottles may be filled from the bucket. Care should be taken not to stir sediments at the bottom of the channel.

Given the extremely low detection limits that laboratory analytical instruments can achieve, leaching of water quality constituents from the surface of a sample bottle or bailing device can affect the water quality results. Sample bottles of the appropriate material composition for each water pollutant for analysis are usually available from the analytical laboratory. Depending upon the pollutant to be analyzed, sample bottles, bailers and discrete-depth samplers should be made of stainless steel, Teflon™ coated plastic, or high-density polyethylene. When in doubt, a laboratory analyst should recommend an appropriate material type for the collection device.

In general, manual grab sampling is generally less practical than automated monitoring for large-scale programs (e.g., monitoring programs involving large numbers of sites or multiple storm events). It is difficult to collect true flow-weighted composites using manual grab sampling methods. In theory one could collect a series of grab samples at short time intervals throughout the course of a storm event to develop an estimate of event mean concentration and pollutant loads. This would require that the series of grab samples be analyzed individually to assess the rise and fall of pollutant concentrations during a storm and to estimate event mean concentrations of pollutants. However this approach of manually collecting grab samples throughout a storm adds significantly to labor costs; consequently automated sampling techniques are typically conducted when event mean concentration of a pollutant is required.

What is the event-mean concentration?

The term "event mean concentration" is a statistical parameter used to represent the flow-proportional average concentration of a given water quality pollutant during a storm event. It is defined as the total pollutant mass divided by the total runoff volume during a single storm event. The calculation of event mean concentration is performed from individual discrete samples taken during the course of storm event. When combined with flow measurement data, the event mean concentration can be used to estimate the total pollutant loading from a given storm event.

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Surface Water Automated Sampling Techniques and Equipment

Automated sampling techniques are the most common method for collecting individual discrete samples or mixed composite samples throughout the duration of a storm event. To conduct a water quality monitoring program using automated sampling techniques, two devices are needed:

1. The mechanical automated sampler unit itself, and
2. A "trigger" device that alerts the automated sampler when to take a sample (typically an open channel flow monitoring device, but automated samplers can also be configured to take samples based upon rain gage or level sensor data.)

What is a flow-weighted composite sample?

A composite sample is a mixture of individual discrete samples. When the individual discrete samples are collected at known flow volumes increments over time, the samples collected are referred to as a "flow weighted" samples. When individual "flow weighted" samples are mixed together to form a larger sample, this larger mixed sample is referred to as a "flow-weighted composite sample".

Automated sampling techniques are generally the preferred method for collecting flow weighted composite samples for calculating individual pollutant event mean concentrations and ultimately the pollutant removal effectiveness of the GSI facility. This is primarily because automated sampling can be programmed to collect individual samples at known flow increments throughout long duration storm events in lieu of the continuous human labor required for many individual manual grab samples throughout the same storm event. Furthermore, it is difficult to predict when a storm event will begin. To collect samples using manual grab sampling techniques, mobilization efforts may be a logistical challenge and costly, especially if the storm event occurs during paid overtime hours for the field staff. For automated sampling techniques, equipment is typically prepped prior to the storm event, readied for sampling at the GSI facility, and secured safely at the facility until after the storm event and samples are retrieved. In general, while automated sampling techniques require additional equipment and are more complicated to program and configure initially, they require less manpower coordination and mobilization efforts during the sampling storm event in the long run as compared to manual grab sampling programs.

Most automated sampler units generally consist of a programming unit capable of controlling sampling increment rate and sample volume based upon an input variable such as flow, an intake port and intake tubing line for collecting the sample, a peristaltic pump for retrieving the sample, a rotating controllable arm capable of distributing samples into individual laboratory sample containers, and a housing unit capable of withstanding tampering and moisture.

The programming units in an automated sampler can be configured to collect samples using various methodologies. For example, samples can be collected at a specific time, at a specific time interval, or upon a received signal from a flow meter or other device (e.g., pH, temperature, observed level data and observed rainfall). The programming unit can also be configured to distribute individual samples into either a single bottle at the center of the housing unit or into

smaller separate bottles which can be analyzed individually or mixed in to larger composite samples.

There are several manufacturers of automated sampler units commercially available. Some examples include: Hach, Manning Environmental Inc, and Teledyne ISCO. Typical cost per sampler is typically around $3000 - $4,000 depending manufacturer and added features. Power for automated samplers are typically either battery or AC.

Surface Water Continuous Water Quality Monitoring and Equipment

Several water quality parameters can be measured using continuous water quality monitoring multi-parameter sondes. A sonde is water quality monitoring instrument that can detect and record in real-time the magnitude or concentration of various water quality parameters at user defined time increments. Most monitors use probes that provide a controlled environment in which a physical and/or electrochemical reaction can take place. The rate of this reaction is typically driven by the concentration of the target constituent in the flow. The rate of reaction, in turn, controls the magnitude of the electrical signal sent to the display or a data-logging device.

Probes are currently available on the market to detect and measure the following water quality parameters:

Temperature	Turbidity	pH	Oxidation-Reduction Potential	Conductivity	Dissolved Oxygen
Ammonium	Ammonia	Nitrate	Salinity	Specific Conductance	Resistivity

Instruments can be configured to measure the magnitude or concentrations of several of these parameters simultaneously (i.e., multi-parameter probes) and provide data logging and PC compatibility.

Despite the advantage of these instruments for measuring near-continuous data, continuous water quality monitoring sondes require frequent inspection and maintenance in the field to prevent loss of accuracy due to fouling by oil and grease, adhesive organics, and bacterial and algal films. The major limitation for the use of continuous water quality sondes in GSI facilities is that many probes are designed to operate while continually submerged in water and exposure of the probe surface to air should be minimized. Often in many locations in GSI facilities limiting exposure to air may be difficult, especially during summer months with long durations between storm events.

There are several manufacturers of continuous water quality sondes commercially available. Some examples include: In-Situ Inc., YSI Inc, and OTT Hydromet. Prices widely vary depending on manufacturer and desired functionality (number of probes, communications, data logging, etc.).

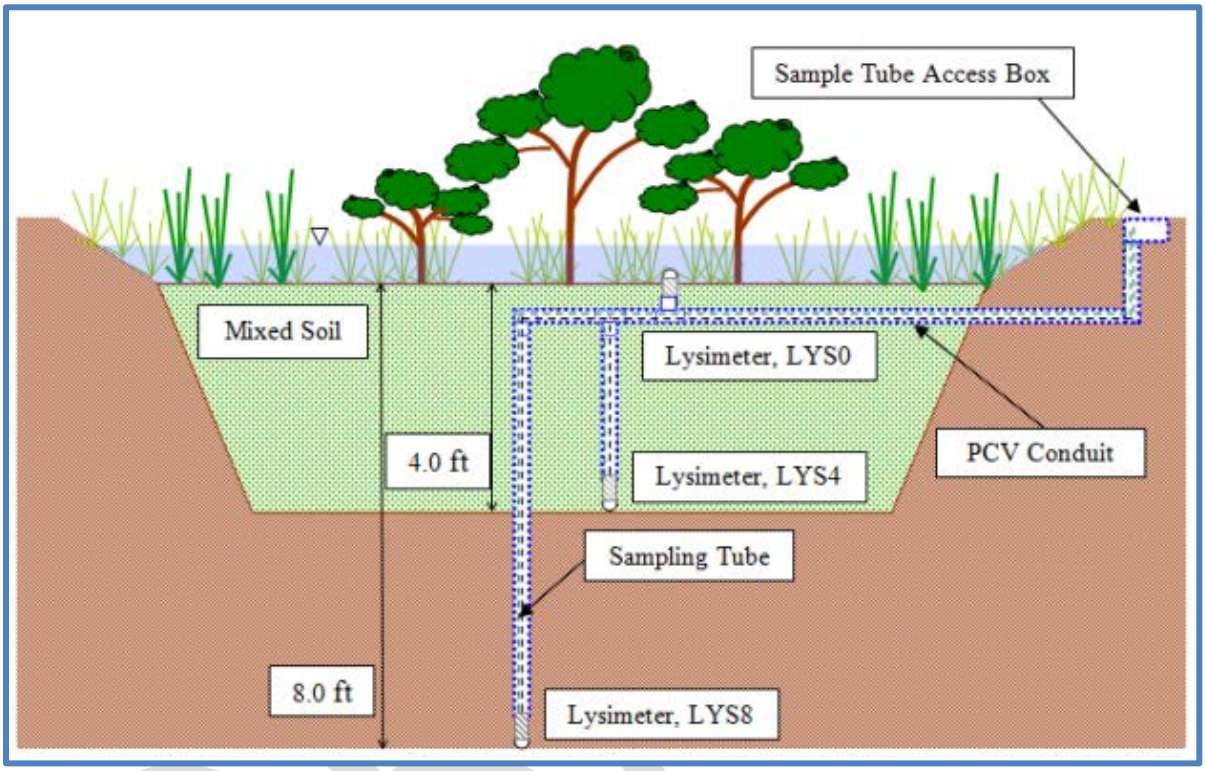
Subsurface Soil Water Quality Monitoring and Equipment

Water quality monitoring can also be performed within the subsurface soils of GSI facilities. The purpose of collecting subsurface soil water quality samples is to detect the presence of pollutants below the GSI facility as a result of infiltration. The most common method for collecting subsurface soil water samples is through the use of pressure/vacuum lysimeters. A pressure/vacuum lysimeter is a cylindrical device consisting of a porous cup (to withdraw and store water from the subsurface soil), a tube to retrieve the sample, a second tube to create a pressure vacuum within the cylindrical porous cup, and a stopper assembly that connects the ends of tubing to the porous cup. The porous cup and tubing system are made of various materials including nylon, ceramic, high density polyethylene and Teflon based upon the water quality monitoring requirements.

A lysimeter works by creating a vacuum or negative pressure greater than the soil suction holding the water within the capillary spaces. The negative pressure inside the lysimeter creates a hydraulic gradient allowing for the water to flow through the porous cup for retrieval via the

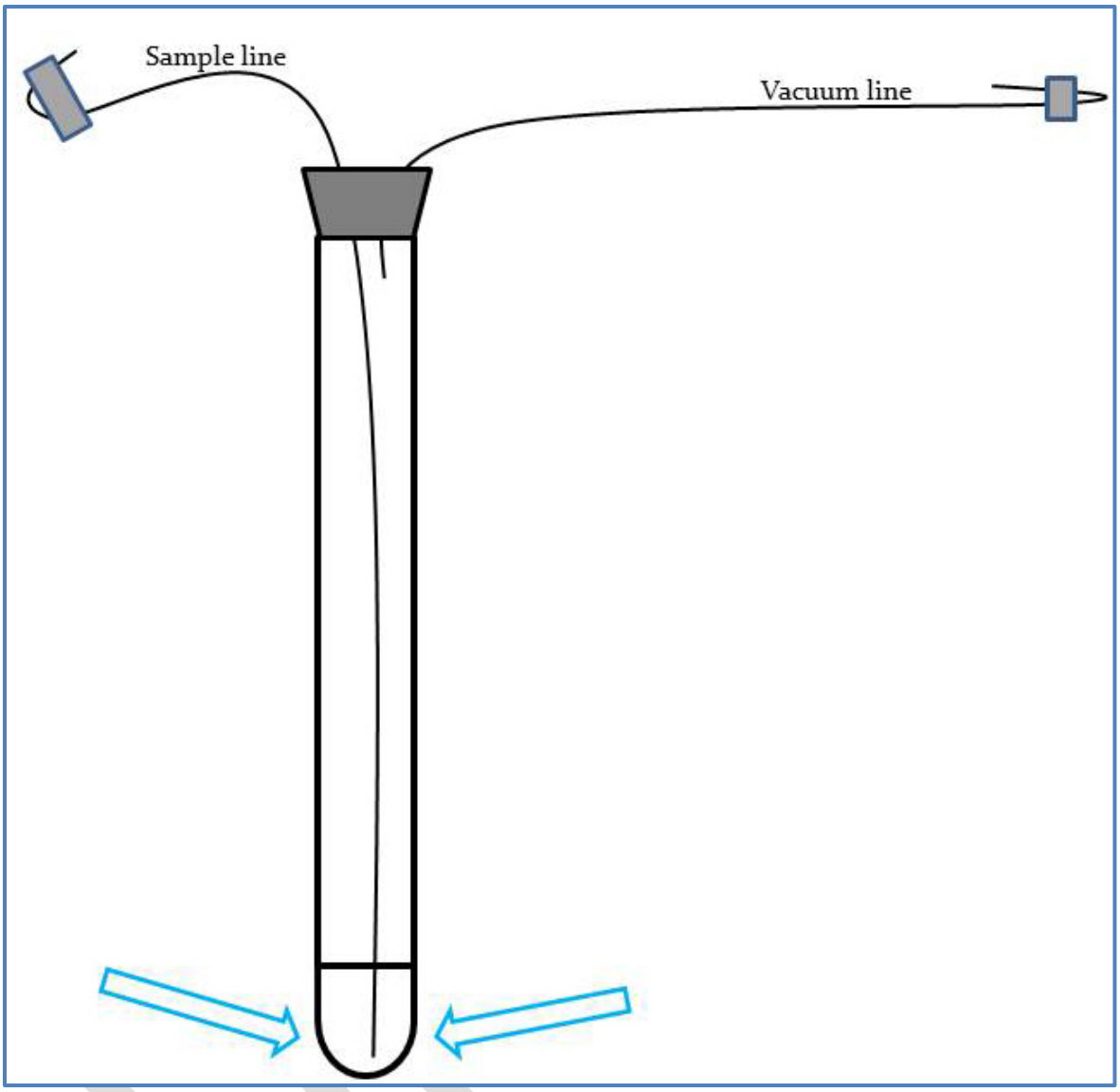
sample tubing. Typically a hand pump is used to create the vacuum pressure and retrieve the sample.

Lysimeters units are typically installed in various depth increments below the surface of the GSI facilities. For example, lysimeters are often installed just below the surface, at 4 feet, and at 8 feet within the subsurface soil layers as depicted below.



There are several manufacturers of subsurface soil water sampling lysimeters commercially available. Some examples include: Decagon Devices, Inc. and Soilmoisture Equipment Corp. Typical cost per lysimeter is approximately $500 - $1000 depending on the water quality requirements and the material of the lysimeter.

A maintenance concern for lysimeters are that fine particles can clog the porous cup over time and prevent adequate sample collection. It is recommended that lysimeters are flushed on occasion and the lowest possible vacuum pressure is applied to the lysimeter to obtain required sample volume. Applying vacuum to the lysimeter should be done roughly 12 hours prior to the start of the water quality sampling storm event.


Sample line
Vacuum line

4.4 Sample Collection Handling and Laboratory Testing

Sample collection handling and laboratory testing procedures are vital to obtaining accurate water quality data. It is recommended that a laboratory quality assurance/quality control (QA/QC) plan be developed at each GSI facility for properly handling samples and conducting laboratory testing. The QA/QC plan should serve as a central document for use by all field and laboratory staff to refer throughout the duration of the water quality monitoring program. The QA/QC plan would complement the Standard Operating Procedures (SOP) document previously referred to in Section 4.3. Ideally, the QA/QC plan should be prepared by someone with a good understanding of chemical analytical methods, field sampling procedures, and data validation procedures from an accredited water quality analytical laboratory. The analytical laboratory should provide its input to ensure the plan is realistic and consistent with the laboratory's operating procedures.

A typical laboratory QA/QC plan for GSI water quality monitoring should include the following sections:

1. Project Description
2. Project Organization and Responsibilities
3. Field Methods
   - sample collection methods
   - field QA procedures such as equipment cleaning and blanks
   - collection of field duplicate samples
   - sample preservation methods
   - type of bottles for subsampling
   - chain of custody requirements
4. Laboratory Procedures
   - constituents for analysis
   - laboratory performance standards (e.g., detection limits, practical quantitation limits, objectives for precision, accuracy, completeness)
   - analysis method references
   - frequency and type of laboratory QA samples (e.g., laboratory duplicates, matrix spikes and spike duplicates, laboratory control samples, standard reference materials)
   - chain of custody requirements
   - data reporting requirements
   - data validation procedures
   - corrective actions

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4.5 Recommended Storm Event Water Quality Sampling Criteria

According to the EPA's 1992 NPDES Storm Water Sampling Guidance Document, "representative" storms should be monitored for stormwater quality compliance. As defined within Section 2.7.1 of the document, a "representative" storm yields the following characteristics:

- The depth of the storm must be at least 0.1 inch of precipitation;
- The storm must be preceded by at least 72 hours of dry weather; and,
- Where feasible, the depth of rain and duration of the event should not vary by more than 50 percent from the average depth. For the Pittsburgh Region, using rainfall record data from 1952-2013 from the Pittsburgh Regional Airport, the average rain event for all storms greater than 0.05 inches of rainfall is equal to 0.25 inches of rainfall depth.

Programs that are not part of the NPDES permit application process or in fulfillment of an NPDES permit may have other requirements.

In general, it is desirable to monitor a broad range of storm conditions rather than just "representative" storms as they are really not representative in many cases. For example, in the Pittsburgh Region where on average it experiences 151 days of precipitation annually according to NOAA, it is often difficult to identify storms where there has been a continual 72- hour dry period prior to the potential water quality sampling event. Acknowledging that storm characteristics are highly dependent on climatic region, EPA's Urban Stormwater BMP Performance Monitoring document recommends the following may be used as a starting point for selecting storm events to conduct water quality monitoring:

- Rainfall Volume: 0.10 inch minimum and No fixed maximum
- Rainfall Duration: No fixed maximum or minimum
- Typical Range: 6 to 24 hours
- Antecedent Dry Period: 24 hours minimum

In general, it is recommended to consult with existing NPDES and MS4 permits relating to "representative storms" for required water quality monitoring. However, additional water quality monitoring outside of these required storm events is encouraged.

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4.6 Reference Watershed Methods

A reference watershed is often used to evaluate the effectiveness of a given GSI facility or multiple GSI facilities of the same type. Many singular GSI facilities do not allow for comparison between inlet and outlet water quality parameters based upon the design layout (i.e. there is no clearly defined inlet or outlet point at which to monitor water quality.) Such is the case with many porous pavement installations and nonstructural GSI facilities (for example, linear bioswales and constructed wetlands). In addition, it is often difficult or costly, where there are many GSI facilities being installed in a watershed to monitor a large number of individual specific locations.

The difficulty in determining the pollutant removal effectiveness of a GSI facility using a reference watershed approach stems from the large number of variables typically involved. When setting up a pollutant monitoring program, it is advantageous to keep the watershed characteristics of the reference watershed and the test watershed with the GSI facilities as similar as possible. Unfortunately, finding two watersheds that are similar is often quite difficult, and the usefulness of the data can be compromised as a result. In order to determine the pollutant removal effectiveness of a GSI facility based on a reference watershed, an accurate accounting of the variations between the watersheds, and operational and environmental conditions is needed.

The most typical parameter used to normalize watershed characteristics using reference watershed methodology is land use area. If the ratio of land uses and activities within each watershed is identical, then the pollutant loads from each watershed area can be scaled linearly. Difficulty arises when in the reference watershed the land use does not have the same ratio as the GSI watershed. In this case, either the effects of land use must be ignored (if nearly similar) or a portion of the load found for each event must be allocated to a land use and then scaled linearly as a function of the area covered by that land use. The effect of the total impervious area is relevant and should always be reported in reference watershed pollutant monitoring. The ratio of the total impervious areas can be used to scale event loads. Caution should be made when attempting reference watershed methods from poorly matched watersheds; poorly matched watersheds can often yield poor results. As the characteristics of the two watersheds diverge, the pollutant removal effectiveness of the GSI facility can be masked by the large number of variables in the system.

Reference watershed methodology also requires incorporation of operational details of each watershed, (e.g., frequency of street sweeping, park maintenance activities, GSI maintenance activities, construction/development/land disturbance activities). Reference watershed pollutant monitoring studies should always provide a record keeping of these activities including the frequency and extent of activities.

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Section 5.0 – Quantifying Collection System Flow Reduction Benefits and Combined Sewer Overflow

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5.1 The Importance of Quantifying Collection System Flow Reduction Benefits

One of the fundamental purposes of constructing green infrastructure is to intercept, capture, and store surface runoff prior to entering traditional gray infrastructure such as stormwater inlets and below ground collection system piping. Storing surface runoff in green infrastructure facilities thereby reduces the peak runoff and total volume contributing to the collection system. If the green infrastructure facility is located in a combined sewer service area, the reduced peak flows and volume to the collection system may result in a realized reduction in combined sewer overflow downstream.

This chapter outlines how to monitor collection systems and quantify the collections system flow reduction benefits from the installation of green infrastructure facilities.

5.2 Identifying Appropriate Locations for Monitoring Flow Reduction and Quantifying GSI Collection System Flow Reduction Benefits

Assessing flows and the potential reductions from green infrastructure within collection systems primarily consists of open channel area-velocity flow monitoring within the neighboring subsurface collection system. Area-velocity flow meters continuously monitor the change in water level and velocity in a pipe at a desired recording time increment. The recorded area and velocity readings can then be converted to a corresponding flow rate using Q=VA. For more information on open channel area-velocity meters refer to Section 3.2 of this manual.

Prior to installing area-velocity flow meters to quantify collection system flow reductions, it is critical to identify appropriate locations that are most advantageous for successful data collection and ultimately meaningful results. While no two green infrastructure locations are identical, it is important to understand the following conditions prior to installing flow monitoring equipment:

1. The size of the green infrastructure facility desired for monitoring compared to the total flow monitoring drainage area of the upstream servicing collection system,
2. The hydraulics and connectivity of the collection system that services the green infrastructure facility desired for monitoring, and
3. The distance to the nearest combined sewer overflow from the green infrastructure facility and the associated rainfall events which trigger activation (if monitoring combined sewer overflow reduction effectiveness).

The following discusses each of the three items listed above, and the most suitable conditions for successful and meaningful collection system flow data collection.

Item 1: The Size of the GSI Facility Compared to the Total Flow Monitoring Drainage Area

The size of the green infrastructure facility compared to the total upstream collection system flow monitoring drainage area is a critical for being able to assess the effectiveness of green infrastructure at reducing flows within the collection system. To assess this item the following should be calculated:

1. The total impervious area managed by the green infrastructure facility(s), and

2. The total impervious area that contributes to the open channel area-velocity flow meter for installation within the collection system.

Figure 5.2 depicts an example of these impervious areas for an example green infrastructure monitoring location in Pittsburgh's Bakery Square. In this example, the total impervious area managed by green infrastructure would be equal to 6 acres and the total impervious area that contributes to the flow meter would be 20 acres.

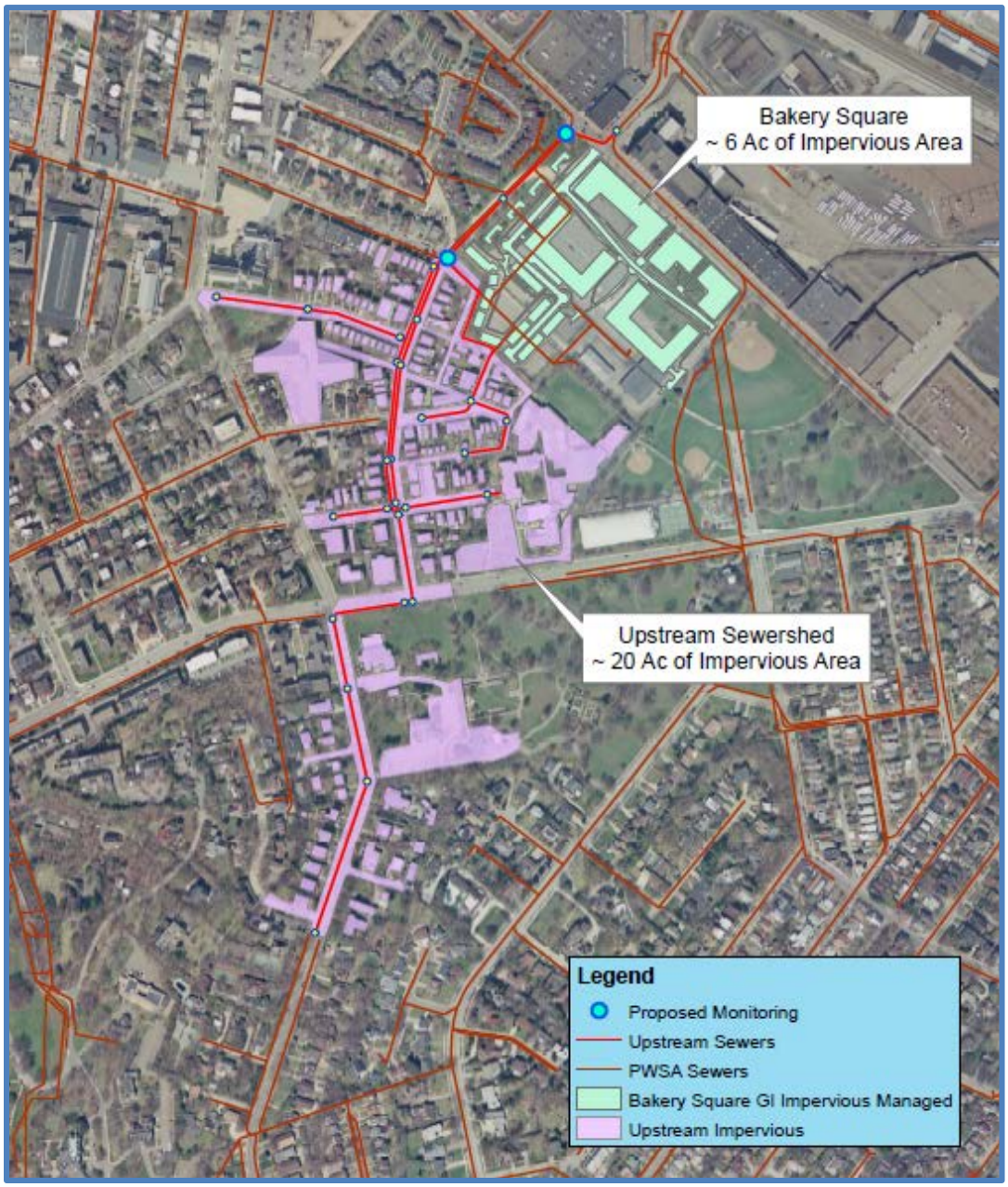

Figure 5.2. Comparison of the Green Infrastructure Impervious Drainage Area to the Collection System Area-Velocity Meter Drainage Area

The total calculated impervious drainage area of the green infrastructure facility(s) and the total calculated impervious drainage area of the collection system flow monitor should be compared. Ideally the impervious area of the green infrastructure facility(s) should be greater than or equal to at least 10% of the total impervious area of the collection system area-velocity flow meter. 10% was chosen as a target benchmark due to the typical manufacturer's reported accuracy of an open channel area-velocity flow meter. Most manufacturers of open channel area-velocity flow meters report accuracies of ± 5% within the velocity sensors. It is important that the flow volume contributing to the green infrastructure facility is large enough to be noticeable within the downstream collection system flow meter and is also larger than the error accuracy of the open channel area-velocity flow meter itself. This will ensure that meaningful and quantifiable results due to the green infrastructure facility are collected by the area-velocity flow meter.

Item 2: The Hydraulics and Connectivity of the Collection System Targeted for Monitoring

The hydraulics of the collection system that services the green infrastructure facility(s) should be fully understood before proceeding with the installation of area-velocity flow meters. The collection system hydraulics should be conducive for collecting accurate area-velocity flow measurements with minimal turbulence. Preferable conditions should include the following:

- Water level sensor readings should be greater than 1 inch,
- Velocity sensor readings should be between 2 and 8 feet per second,
- Monitoring drop manholes should be avoided,
- Areas of observed or suspected turbulence in the collection system should be avoided. Examples include incoming drops from side connections, offset joints, bends in sewer, or other flow turbulences caused pipe/manhole deficiencies,
- Areas with observed or suspected heavy debris should be avoided,
- Monitoring inlet sewers of manholes is preferable over the outlet sewer of manholes,
- In challenging flow locations such as combined sewer overflow structures with weirs, leaping weirs and gate structures, redundant depth sensors and/or multiple flow meters may be required.

Before installing an area-velocity flow meter, the conditions described in the above bulleted list should be investigated within the collection system proposed for flow monitoring. If any of the above conditions are not met, the proposed flow monitoring location should be reconsidered for collecting flow data.

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Level of Ideal for Open Channel Area-Velocity Flow Metering

Item 3: The Proximity to the Nearest Combined Sewer Overflow and Activation Characterization

The proximity and activation behavior of the nearest combined sewer overflow should be understood if quantifying the overflow reduction is a goal of the green infrastructure flow monitoring data collection efforts. The nearest downstream combined sewer overflow location should be identified prior to installing the area-velocity flow meters. Once the combined sewer overflow location is identified the following should be calculated:

1. The total impervious area upstream to the combined sewer overflow diversion compared to the impervious area of the green infrastructure facility(s), and
2. The activation behavior of the combined sewer overflow diversion including: minimum observed rainfall event to trigger combined sewer overflow activation, typical overflow volume on a storm event basis, and the number of activations in a typical year.

The total calculated impervious drainage area of the combined sewer overflow to be monitored and the total calculated impervious area of the green infrastructure facility(s) should be compared in the same fashion as previously described in Item 1. Ideally the impervious area of the green infrastructure facility(s) should be greater than or equal to at least 10% of the total impervious area of the combined sewer overflow diversion impervious drainage area. 10% was chosen as a target benchmark due to the typical manufacturer's reported accuracy of an open channel area-velocity flow meter. Most manufacturers of open channel area-velocity flow meters report accuracies of ± 5% within the velocity sensors. It is important that the flow volume contributing to the green infrastructure facility is large enough to be noticeable providing the ability to quantify potential combined sewer overflow reductions at the diversion structure. Furthermore it is also important that the measured flow reductions from the green infrastructure facility are larger than the error accuracy of the open channel area-velocity flow meter itself. This will ensure that meaningful and quantifiable results due to the green infrastructure facility are collected by the area-velocity flow meter.

The activation behavior of the combined sewer overflow is also important to understand prior to installing area-velocity flow meters to quantify overflow reductions. These include the minimum

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observed rainfall event for activation, typical overflow volume on a storm event basis, and the number of activations in a typical year. Most green infrastructure facilities are designed to manage the first 0.75 to 1.5 inches over the contributing impervious drainage area. The minimum event activation of the combined sewer overflow diversion should be understood and compared to the design size of the green infrastructure facility(s) upstream. The lower the minimum rainfall depth event to trigger overflow activation, the more likely the green infrastructure facility(s) will be effective at reducing overflow. In this scenario, the area-velocity flow meters installed the combined sewer overflow diversion will produce more noticeable and quantifiable overflow reduction results. A scatter plot is typically generated to analyze the minimum rainfall depth event to trigger combined sewer overflow activation. An example scatterplot is shown in Figure 5.3. This type of plot should be generated and analyzed prior to installing flow monitoring devices at the combined sewer overflow diversion. The number of activations, the volume of the activations, and the minimum rainfall depth to trigger activation during a typical year should be understood for the proposed combined sewer overflow monitoring location.

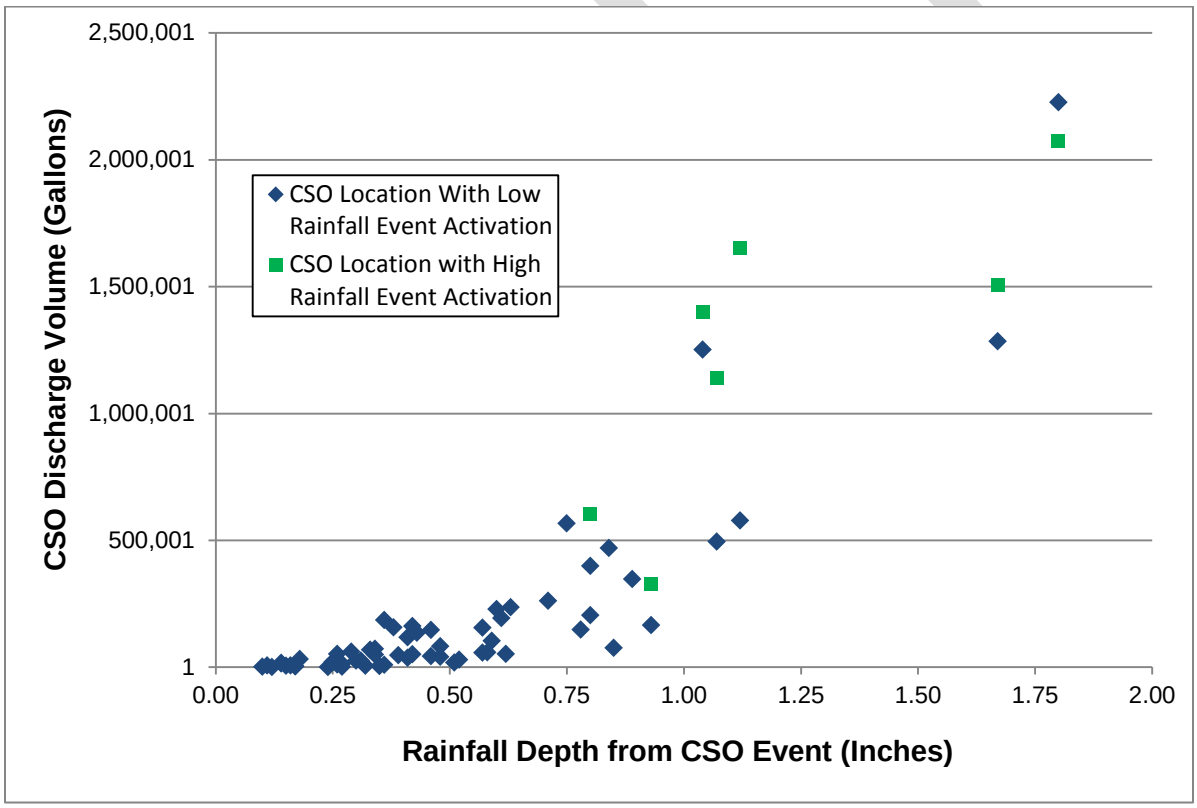

Figure 5.3. CSO Activation Plot for a Low Rainfall Event Activation CSO and a High Rainfall Event Activation CSO

By plotting out the overflow activation events, one can easily determine if the combined sewer overflow location is a good candidate for quantifying reductions from green infrastructure. From Figure 5.3 it is shown that the blue combined sewer overflow location would potentially yield more noticeable and quantifiable overflow reduction results if monitored. This is because: 1.)

there are many more events less than 1 inch in rainfall that produce overflow activation, 2.) the minimum rainfall event which triggers an combined sewer overflow activation is much smaller, and 3.) the total volume of the combined sewer overflow during the typical year is much greater. This is not to say that the green combined sewer overflow location cannot be monitored, however it must be taken into account that the overflow activations are not as prevalent and larger rainfall events are required for activation which may result in a longer monitoring period and ultimately more cost to the study.

To generate plots such as the one shown in Figure 5.3 it is recommended that an existing conditions typical year hydrologic and hydraulic model simulation be performed for the combined sewer overflow diversion considered for monitoring. The overflow results from the typical year simulation should be disaggregated for each simulated rain event within the typical year. The modeled overflow volume and associated total rainfall depth for each rain event can then be plotted.

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5.3 Step-By-Step Procedure for Collection System Flow Reduction Green Infrastructure Monitoring

The following section outlines two methodologies for quantifying collection system flow reduction benefits from the construction of green infrastructure facilities.

Method 1: Post-Construction Hydraulic and Hydrologic Modeling Performance Reduction Assessment

The following section provides a general step-by-step process for quantifying flow reduction benefits in the collection system from the installation of green infrastructure facilities using a hydraulic and hydrologic modeling approach.

Step 1: Select appropriate green infrastructure facility(s) to monitor based on the information gathered as outlined in Section 5.3. This could be a single green infrastructure facility or could be a collection of facilities in same sewershed.

Step 2: Determine where to place area-velocity flow meters in the collection system based on the information gathered as outlined in Section 5.3. Consider placing meters upstream of the green infrastructure, downstream of green infrastructure, and several thousand feet downstream from area managed (maybe near the combined sewer overflow diversion or the diversion structure itself). Goal is to best understand the change in volume for the proposed monitoring locations.

Step 3: Install flow meters in a favorable hydraulic location as outlined in Section 5.3; Recommended monitoring duration should be for at least 6 months or multiple rainfall events.

Step 4: Update existing hydrologic and hydraulic model with the collected flow monitoring data and the green infrastructure facilities. – “Modeled Post-Construction”

Step 5: Simulate the typical year rainfall with the post-construction hydrologic and hydraulic model from Step 4 to determine post-construction flow reduction performance.

Step 6: Create pre-existing conditions model without the green infrastructure by replacing the green infrastructure with directly connected impervious area to the collection system. – “Modeled Pre-Construction”

Step 7: Simulate the typical year rainfall the pre-construction hydrologic and hydraulic model from Step 6 to determine pre-construction flow reduction performance.

Step 8: Compare the model output from the pre-construction model and post-construction model to evaluate performance of the green infrastructure and the flow reductions realized within the collection system.

Step 9: Compare post-construction model results to site scale green infrastructure monitoring performance, if available.

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Method 2: Pre-Construction and Post-Construction Monitoring Direct Comparison Performance Reduction Assessment

The following section provides a general step-by-step process for quantifying flow reduction benefits in the collection system from the installation of green infrastructure facilities using a direct comparison of flow data collected between pre-construction and post-construction green infrastructure conditions.

Step 1: Prior to the construction of the green infrastructure facility(s), select appropriate location for the placement of area-velocity flow meters in the collection system based on the information gathered as outlined in Section 5.3. Consider placing meters upstream of the planned green infrastructure, downstream of the green infrastructure, and several thousand feet downstream from area (maybe near the combined sewer overflow diversion or the diversion structure itself). Goal is to best understand the change in volume for the proposed monitoring locations.

Step 2: Install flow meters in a favorable hydraulic location as outlined in Section 5.3 to characterize the flow contribution to the collection system during pre-construction conditions; recommended pre-construction monitoring duration should be for at least 6 months or multiple rainfall events.

Step 3: Construct and install green infrastructure in the planned monitoring area. Leave pre-construction flow meters installed during construction and post-construction phases to characterize the flow contributions during post-construction conditions; recommended post-construction monitoring duration should be for at least 6 months or multiple rainfall events.

Step 4: Calculate the runoff generated for the pre-construction and post-construction conditions for each observed rainfall event and normalize total runoff by the total rainfall over the flow meter drainage area. This value is often referred to as the “effective rainfall” or “R-Coefficient” of the drainage area.

Step 5: Directly compare the R-Coefficients from pre-conditions from post-conditions to determine the collection system reduction benefits of total runoff removed from the system.

Step 6: Update the existing hydrologic and hydraulic model for both the collected pre-construction and post-construction flow data. Simulate the typical year rainfall in the model for under both pre-construction conditions and post-construction conditions to determine additional collection system benefits such as peak flow reduction and combined sewer overflow reduction (if combined sewer overflow not directly monitored).

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