Urban Stormwater BMP Performance Monitoring

Prepared by
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Wright Water Engineers, Inc.

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EXECUTIVE SUMMARY

Over the past three decades, both public and private entities have monitored urban stormwater Best Management Practices (BMPs) for many purposes, often related to efforts to comply with the continually evolving federal Clean Water Act. In 1996, the U.S. Environmental Protection Agency (EPA) entered into a cooperative agreement with the American Society of Civil Engineers (ASCE), led by members of the Urban Water Resources Research Council (UWRRC), to initiate the International Stormwater BMP Database ("BMP Database") project. The BMP Database goals were multifaceted, with key goals including development of a standardized set of monitoring and reporting protocols for urban stormwater BMP performance studies and assembling and summarizing historical and on-going BMP study data into a standardized format to facilitate performance analysis. During the initial stages of the BMP Database project, it became clear that better guidance was needed regarding stormwater BMP monitoring, particularly if monitoring results were to be valuable to the broader technical, management, and regulatory community. As a result, the 2002 version of this monitoring manual was developed to promote collection of more useful and representative data associated with BMP studies, as well as more consistent reporting of monitoring results appropriate for inclusion in the BMP Database. Since that time, both the BMP Database project and stormwater management practices have continued to evolve, prompting this second release of the manual.

The purposes of this updated Manual are primarily twofold:

1) Improve the state of the practice by providing and enhancing a recommended set of protocols and standards for collecting, storing, analyzing, and reporting stormwater BMP monitoring data that will lead to better understanding of the function, efficiency, and design of urban stormwater BMPs.

2) Provide monitoring guidance for "Low Impact Development" (LID) strategies at the overall site level (e.g., monitoring overall sites with multiple distributed stormwater controls).

The audience for this Manual is targeted primarily to those who possess a basic level of knowledge regarding stormwater quality, hydrology, and regulatory issues. The EPA website (www.epa.gov) and other state and local websites can be referenced for additional guidance and background information.

This Manual provides guidance for all stages of BMP monitoring programs ranging from the early stages of study design to the end stages of data interpretation and reporting. Guidance is provided for monitoring a broad range of individual BMPs as well as overall site monitoring with multiple distributed BMPs, such as is the case with LID sites. This Manual focuses primarily on the collection, reporting, and analysis of water quantity and quality measurements at the heart of quantitative BMP efficiency projects. It does not address in detail sediment sampling methods and techniques, biological assessment, monitoring of receiving waters, monitoring of groundwater, streambank erosion, channel instability, channel morphology, or other activities that in many circumstances may be as, or more, useful for measuring and monitoring water quality for assessing BMP efficiency. In some cases, references for additional information on these subjects have been provided. The Manual focuses on these topics:

1) Designing the Monitoring and Reporting Program (Chapter 2): A well-thought out and systematically designed monitoring program is essential to a cost-effective study design that yields meaningful results. The Manual builds upon guidance provided by EPA (2002) in its *Guidance for Quality Assurance Project Plans,* providing additional guidance specific to stormwater BMP monitoring and the BMP Database protocols.

2) Methods and Equipment for Stormwater BMP Monitoring (Chapters 3 and 4): In order to obtain high-quality data in BMP monitoring studies, it is necessary to select the proper precipitation, flow, and water quality sample collection and monitoring equipment and procedures. Chapter 3 provides information and guidance related to flow and precipitation monitoring in the context of BMP monitoring, and Chapter 4 focuses on water quality sample collection and analysis methods.

3) Implementing the Monitoring Program (Chapter 5): In order for well designed monitoring programs to result in high quality data, personnel must be properly trained, equipment properly installed, calibrated and maintained, samples correctly collected and analyzed, and data properly reported. Failures at this stage of the monitoring program can result in data that cannot be used to draw valid conclusions regarding BMP performance.

4) Data Management, Evaluation and Reporting of Results (Chapter 6): Once data have been collected from a monitoring program, the data need to be compiled and managed in a manner that reduces introduction of errors and enables ready access for future reference, and ideally, facilitates incorporation into the BMP Database (www.bmpdatabase.org). A strong data management and reporting system helps to ensure that studies are documented in a manner that enables long-term use of the data and transferability to the local, regional, national, and international state of the practice. As part of this chapter, an overview of data reporting requirements for the BMP Database is provided, describing study features such as test site, watershed, and BMP design characteristics, instrumentation, and monitoring data (precipitation, flow, water quality).

5) BMP Performance Analysis (Chapter 7): Over the past decade, the BMP Database project has developed recommended performance analysis approaches for BMP studies. This chapter describes these methods, as well as pitfalls to avoid misleading interpretation of data.

6) Low Impact Development(LID)/Distributed Controls Monitoring (Chapter 8): Building upon the concepts introduced for monitoring individual BMPs, this chapter provides guidance on specific challenges associated with monitoring distributed controls at the site level, particularly focused on LID. In these types of studies, a variety of practices such as amending soils to promote infiltration of runoff,

disconnecting impervious areas, use of pervious paving materials, implementation of rain gardens on multiple lots, use of swales instead of curb and gutter, and other runoff reduction practices may be implemented. As a result, unique challenges exist in collecting and analyzing the performance of such sites. Although the state of the practice continues to evolve on this topic, this chapter provides basic guidance on properly designing such studies and suggests approaches for meaningful data interpretation.

7) Data Interpretation and Performance Evaluation of LID Studies (Chapter 9): The careful interpretation and evaluation of data is critical in reaching appropriate conclusions about volume reduction and the water quality benefits of LID. Chapter 9 suggests approaches to interpret and evaluate hydrologic and water quality data, both absolutely and in comparison to conventional BMP implementations. Although LID and conventional BMP studies have some similarities, there are also some key differences that warrant LID-specific guidance. A few representative differences include: LID strategies tend to emphasize reduction in volume rather than reduction in concentration; LID studies are less likely to have an "influent stream" conducive to inflow-outflow comparisons; and the time scale of monitoring required to obtain representative data may be much longer than for a conventional studies.

8) LID Case Studies (Chapter 10): This chapter summarizes key aspects of site-level LID studies conducted in Cross Plains, WI; Burnsville, MN; Jordan Cove, CT; and Somerset, MD. All of these studies are based on a paired watershed approach incorporating a reference and test watershed, either geographically or over time.

9) Supplemental Resources on Key Topics (Appendices): Many of the topics addressed in this manual are complex and/or require considerable detail for proper discussion. For this reason, supplemental appendices are provided as follows:

   - Appendix A: Data Entry Forms for International Stormwater BMP Database: Forms useful for recording BMP monitoring study information, key watershed and BMP design criteria, instrumentation and monitoring data for precipitation, flow, and water quality are summarized in Appendix A, corresponding to the data entry spreadsheets used in the BMP Database. The Stormwater BMP Database website (www.bmpdatabase.org) should be referenced to obtain the most current version of these spreadsheets for data entry.

   - Appendix B: Comparison of Data Analysis Approaches: This appendix contains a discussion of the various BMP performance analysis approaches that have been commonly used historically, but are not currently recommended by the BMP Database project. Nonetheless, some of these techniques are used by others, so comments are provided regarding the strengths and weaknesses of each approach.

   - Appendix C: Determining Required Number of Samples: Depending on the objectives established for the monitoring program, the number of samples required for meaningful interpretation of the data can vary substantially. This appendix provides guidance in determining the number of samples needed to obtain statically significant monitoring data. It also includes charts for estimating the number of samples required to observe a statically significant difference between two populations for a various levels of confidence and power.

- Appendix D: Error Analysis: Properly accounting for errors and uncertainty in BMP monitoring data is important to avoid erroneous conclusions regarding BMP performance. This appendix describes methods for calculating expected errors in field measurements.

- Appendices E and F: Statistical Information: Although this manual does not provide a primer on statistics, Appendix E provides some basic information needed to properly apply statistics in the context of stormwater BMP monitoring. For example, a table for estimating arithmetic descriptive statistics based on descriptive statistics of log-transformed data is included. Appendix F provides basic information related to log-normal distributions.

This Manual addresses methods that were in use at the time it was written. As the state of the practice and the design of monitoring equipment progress, new monitoring approaches and techniques, more sensitive devices, and equipment based on new technologies will likely be employed. Although the technology may change somewhat from that described herein, most of the basic flow and water quality monitoring methods discussed in this document have a long history of use and will most likely remain viable even as new and different technologies emerge.

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Chapter 1
INTRODUCTION

1.1 Purpose of this Manual

Over the past three decades, both public and private entities have monitored urban stormwater Best Management Practices (BMPs) for many purposes, often related to efforts to comply with the continually evolving federal Clean Water Act. In 1996, the U.S. Environmental Protection Agency (EPA) entered into a cooperative agreement with the American Society of Civil Engineers (ASCE), led by members of the Urban Water Resources Research Council (UWRRC), to initiate the International Stormwater BMP Database project ("BMP Database"). The BMP Database goals were multi-faceted, with key goals including development of a standardized set of monitoring and reporting protocols for urban stormwater BMP performance studies and assembling and summarizing historical and on-going BMP study data into a standardized format to facilitate performance analysis. During the initial stages of the BMP Database project, it became clear that better guidance was needed regarding stormwater BMP monitoring, particularly if monitoring results were to be valuable to the broader technical, management, and regulatory community. As a result, the 2002 version of this monitoring manual was developed to promote collection of more useful and representative data associated with BMP studies, as well as more consistent reporting of monitoring results appropriate for inclusion in the BMP Database. Since that time, both the BMP Database project and stormwater management practices have continued to evolve, prompting this second release of the manual.

The purposes of this updated Manual are primarily two-fold:

1) Improve the state of the practice by providing and enhancing a recommended set of protocols and standards for collecting, storing, analyzing, and reporting stormwater BMP monitoring data that will lead to better understanding of the function, efficiency, and design of urban stormwater BMPs.

2) Provide monitoring guidance for "Low Impact Development" (LID) strategies at the overall site level (e.g., monitoring overall sites with multiple distributed stormwater controls).

The remainder of this introduction provides a brief synopsis of the organization and content of this Manual, and provides some basic information on stormwater, BMPs, the BMP Database project, and regulatory drivers related to BMP implementation and monitoring. Several key terms used throughout this manual are defined, and links to other monitoring resources are also provided.

1.2 Manual Overview

This Manual provides guidance for all stages of BMP monitoring programs ranging from the early stages of study design to the end stages of data interpretation and reporting. Guidance is provided for monitoring a broad range of individual BMPs as well as overall site monitoring with multiple distributed BMPs, such as is the case with LID sites. The Manual addresses these topics:

1) Designing the Monitoring and Reporting Program (Chapter 2): A well-thought out and systematically designed monitoring program is essential to a cost-effective study design that yields meaningful results. The Manual builds upon guidance provided by EPA (2002) in its *Guidance for Quality Assurance Project Plans,* providing additional guidance specific to stormwater BMP monitoring and the BMP Database protocols.

2) Methods and Equipment for Stormwater BMP Monitoring (Chapters 3 and 4): In order to obtain high-quality data in BMP monitoring studies, it is necessary to select the proper precipitation, flow, and water quality sample collection and monitoring equipment and procedures. Chapter 3 provides information and guidance related to flow and precipitation monitoring in the context of BMP monitoring, and Chapter 4 focuses on water quality sample collection and analysis methods.

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4) Data Management, Evaluation and Reporting of Results (Chapter 6): Once data have been collected from a monitoring program, the data need to be compiled and managed in a manner that reduces introduction of errors and enables ready access for future reference, and ideally, facilitates incorporation into the BMP Database (http://www.bmpdatabase.org). A strong data management and reporting system helps to ensure that studies are documented in a manner that enables long-term use of the data and transferability to the local, regional, national, and international state of the practice. As part of this chapter, an overview of data reporting requirements for the BMP Database is provided, describing study features such as test site, watershed, and BMP design characteristics, instrumentation, and monitoring data (precipitation, flow, water quality).

5) BMP Performance Analysis (Chapter 7): Over the past decade, the BMP Database project has developed recommended performance analysis approaches for BMP studies. This chapter describes these methods, as well as pitfalls to avoid misleading interpretation of data.

6) LID/Distributed Controls Monitoring (Chapter 8): Building upon the concepts introduced for monitoring individual BMPs, this chapter provides guidance on specific challenges associated with monitoring distributed controls at the site level, particularly focused on LID. In these types of studies, a variety of practices such as disconnecting impervious areas, use of pervious paving materials, implementation of rain gardens on multiple lots, use of swales instead of curb and gutter, and other runoff reduction practices may be implemented. As a result, unique challenges exist in collecting and analyzing the performance of such sites. Although the state of the practice continues to evolve on this topic, this chapter provides basic guidance on properly designing such studies.

7) Data Interpretation and Performance Evaluation of LID Studies (Chapter 9): The careful interpretation and evaluation of data is critical in reaching appropriate conclusions about volume reduction and the water quality benefits of LID. Chapter 9 suggests approaches to interpret and evaluate hydrologic and water quality data, both absolutely and in comparison to conventional BMP implementations. Although LID and conventional BMP studies have some similarities, there are also some key differences that warrant LID-specific guidance. A few representative differences include: LID strategies tend to emphasize reduction in volume rather than reduction in concentration; LID studies are less likely to have an “influent stream” conducive to inflow-outflow comparisons; and the time scale of monitoring required to obtain representative data may be much longer than for a conventional studies.

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   - Appendix C: Determining Required Number of Samples: Depending on the objectives established for the monitoring program, the number of samples required for meaningful interpretation of the data can vary substantially. This appendix provides guidance in determining the number of samples needed to obtain statically significant monitoring data. It also includes charts for estimating the number of samples required to observe a statically significant difference between two populations for a various levels of confidence and power.

- Appendix D: Error Analysis: Properly accounting for errors and uncertainty in BMP monitoring data is important to avoid erroneous conclusions regarding BMP performance. This appendix describes methods for calculating expected errors in field measurements.
- Appendices E and F: Statistical Information: Although this manual does not provide a primer on statistics, Appendices E and F provide some basic information needed to properly apply statistics in the context of stormwater BMP monitoring.`

1.3 Stormwater Basics

1.3.1 Physical and Chemical Characteristics of Stormwater Runoff

Numerous studies conducted since the late 1970s show that stormwater runoff from urban and industrial areas is a potentially significant source of pollution (EPA 1983; Driscoll et al. 1990; Pitt et al. 2008). As a result, federal, state, and local regulations have been promulgated to address stormwater quality and many communities have implemented structural and non-structural stormwater BMPs to minimize the potential adverse impacts of urban runoff and comply with these regulations. Although the historical focus of many monitoring programs was primarily stormwater quality (chemical), more recently, the hydrologic and hydraulic (physical) changes in watersheds associated with urbanization are increasingly being recognized as significant contributors to receiving water degradation. Representative physical impacts include stream channel changes (e.g., erosion, sedimentation, temperature changes), as well as wetland water level fluctuations. As a result, site designs such as LID that seek to mimic predevelopment site hydrology are being encouraged or mandated by more communities.

Some of the challenges associated with proper characterization of stormwater quality are related to its highly variable nature (EPA 1983; Driscoll et al. 1990). For example, the intensity of rainfall often varies irregularly and dramatically. These variations in rainfall intensity affect runoff rate, pollutant washoff rate, in-channel flow rate, pollutant transport, sediment deposition and resuspension, channel scour, and numerous other phenomena that collectively determine the pollutant concentrations, pollutant forms, and stormwater flow rate observed at a given monitoring location at any given moment. In addition, the transitory and unpredictable nature of many pollutant sources and release mechanisms (e.g., spills, leaks, dumping, construction activity, landscape irrigation runoff, vehicle washing runoff), and differences in the time interval between storm events also contribute to inter-storm variability. As a result, pollutant concentrations and other stormwater characteristics at a given location often fluctuate greatly during a single storm runoff event and from event to event. It is important that those involved with stormwater monitoring not underestimate the complex variables affecting stormwater BMP monitoring.

Exhibit 1-1. Defining "Stormwater"

Although in the simplest sense, stormwater can be defined as runoff resulting from rainfall or snowmelt, a more inclusive definition is used in this Monitoring Manual. In the context of stormwater BMP monitoring, stormwater also includes base flows or dry weather flows occurring prior to, during and following storm runoff events, as well as other discharges affecting the BMP such as materials that are dumped, leaked, spilled, or otherwise discharged into the conveyance system.

Representative dry weather flows include pavement washing, pavement cutting wash water, or irrigation water, including the pollutants transported in such flows. In some cases, dry weather loads can greatly exceed wet weather loads over the course of a year and must be taken into account in BMP monitoring programs.

Stormwater may also contain materials that settled out in the system toward the end of previous storms and are flushed out by high flows during the event being sampled.

1.3.2 Best Management Practices

In the context of post-construction urban stormwater runoff management, Best Management Practices (BMPs) include a variety of measures intended to prevent or reduce the discharge of pollutants to waters of the United States. BMPs can be discussed in terms of individual structural practices and non-structural practices, as well as in terms of overall site designs such as LID that combine a variety of structural and non-structural practices. Structural BMPs include a variety of practices that rely on a wide range of hydrologic, physical, biological, and chemical processes to improve water quality and manage runoff. (See Exhibit 1-2 and *Critical Assessment of Stormwater Treatment and Control Selection Issues* [WERF 2005] for more information on these processes.) Non-structural BMPs such as education and source control ordinances typically depend on a combination of behavioral change and enforcement.

Due to the variation in BMP designs and features, as well as rainfall distributions, there is not a one-size-fits-all monitoring strategy. For example, Philadelphia, PA, receives approximately 45 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 BMPs and the design of monitoring programs. Many BMPs and LID sites are designed to treat runoff from small storms, rather than large storms, so it is important to understand the basis of design for BMPs when developing monitoring programs and evaluating performance of BMPs. In this Manual, five general categories of BMPs will be used to assist in monitoring strategy design and BMP performance analysis. These general categories include:

Type I	BMPs with well-defined inlets and outlets (e.g., detention basins, vegetated swales, catch basin inserts). These are the “easy” BMPs 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	BMPs with well-defined inlets, but not outlets (e.g., infiltration basins, infiltration trenches, bioretention cells). Monitoring strategies for these BMPs 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	BMPs 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	BMPs without any well-defined inlets or outlets and/or institutional BMPs (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.

In addition to understanding the complexities associated with monitoring the various types of BMPs, it is also important to recognize that there is a difference between reporting performance based on the flows treated by the BMP and the flows associated with the overall BMP system, which includes bypassed flows and overflows. These types of considerations are also important when assessing the performance of the BMP, the effectiveness of the overall BMP system and the efficiency of the BMP or BMP system in removing pollutants. Definitions of several BMP-related terms used throughout this document are provided in Exhibit 1-3.

Exhibit 1-2. Structural Stormwater Controls and Associated Fundamental Process Categories

(Source: WERF 2005. *Critical Assessment of Stormwater Treatment and Control Selection Issues*. 02-SW-1.)

Fundamental Process Category (FPC)	**Unit Operation or Process (UOP)** ***Target Pollutants***	**Typical Treatment System Components (TSCs)**
Hydrologic Operations	Flow and Volume Attenuation	Extended detention basins Retention/detention ponds Wetlands Tanks/vaults Equalization basins
	Volume Reduction *All pollutant loads*	Infiltration/exfiltration trenches and basins Permeable or porous pavement Bioretention cells Dry swales Dry well Extended detention basins
Physical Treatment Operations	Particle Size Alteration *Coarse sediment*	Comminutors (not common for stormwater) Mixers (not common for stormwater)
	Physical Sorption *Nutrients, metals, petroleum compounds*	Engineered media, granular activated carbon, and sand/gravel (at a lower capacity)
	Size Separation and Exclusion (screening and filtration) *Coarse sediment, trash, debris*	Screens/bars/trash racks Biofilters Permeable or porous pavement Infiltration/exfiltration trenches and basins Manufactured bioretention systems Engineered media/granular/sand/compost filters Hydrodynamic separators Catch basin inserts (i.e., surficial filters)
	Density, Gravity, Inertial Separation (grit separation, sedimentation , flotation and skimming, and clarification) *Sediment, trash, debris, oil and grease*	Extended detention basins Retention/detention ponds Wetlands Settling basins, Tanks/vaults Swales with check dams Oil-water separators Hydrodynamic separators
	Aeration and Volatilization *Oxygen demand, PAHs, VOCs*	Sprinklers Aerators Mixers (not common for stormwater)
	Physical Agent Disinfection *Pathogens*	Shallow detention ponds Ultra-violet systems
Biological Processes	Microbially Mediated Transformation (can include oxidation, reduction, or facultative processes) *Metals, nutrients, organic pollutants*	Wetlands Bioretention systems Biofilters (and engineered bio-media filters) Retention ponds Media/sand/compost filters
	Uptake and Storage *Metals, nutrients, organic pollutants*	Wetlands/wetland channels Bioretention systems Biofilters Retention ponds
Chemical Processes	Chemical Sorption Processes *Metals, nutrients, organic pollutants*	Subsurface wetlands Engineered media/sand/compost filters Infiltration/exfiltration trenches and basins
	Coagulation/Flocculation *Fine sediment, nutrients*	Detention/retention ponds Coagulant/flocculant injection systems
	Ion Exchange *Metals, nutrients*	Engineered media, zeolites, peats, surface complexation media
	Chemical Disinfection *Pathogens*	Custom devices for mixing chlorine or aerating with ozone Advanced treatment systems

Exhibit 1-3. Key Terms Used in the Manual

A common understanding of terms used in this manual includes the following:

- Best Management Practice (BMP) – A device, practice, or method for removing, reducing, retarding, or preventing targeted stormwater runoff constituents, pollutants, and contaminants from reaching receiving waters. (Some entities use the terms "Stormwater Control Measure", "Stormwater Control", or "Management Practice", but BMP is used in this manual for consistency with the International Stormwater BMP Database.) BMPs include both LID and non-LID practices,

- BMP System – A BMP system includes the BMP and any related bypass or overflow. For example, the efficiency (see below) can be determined for an offline retention pond either by itself (as a BMP) or for the BMP system (BMP including bypass).

- Low Impact Development (LID) – LID is an overall land planning and engineering design approach to managing stormwater runoff. LID emphasizes conservation and use of on-site natural features to protect water quality. This approach implements engineered small-scale hydrologic controls to mimic the pre-development hydrologic regime of watersheds through infiltrating, filtering, storing, evaporating, and detaining runoff close to its source. LID is similar to Sustainable Urban Drainage Systems (SUDS), a term used in the United Kingdom, and Water Sensitive Urban Design (WSUD), a term used in Australia. The term Green Infrastructure may also be used, particularly in areas with combined sewer overflow (CSO) issues.

- LID Practice – Individual practices used as part of overall LID developments or integrated into traditional developments include practices such as bioretention facilities, rain gardens, vegetated rooftops, rain barrels, permeable pavements and other infiltration-oriented practices. In some cases, LID terminology and traditional BMP terminology vary for the same basic practice. For example, the LID term "bioretention" may also be called porous landscape detention; the LID term "bioswale" may also be called grass swale.

- Performance – measure of how well a BMP meets its goals for stormwater that the BMP *is designed to treat*.

- Effectiveness – measure of how well a BMP *system* meets its goals in relation to *all* stormwater flows.

- Efficiency – measure of how well a BMP or BMP system *removes or controls pollutants*.

1.4 Stormwater BMP Monitoring

Purposes of BMP monitoring vary significantly and the monitoring program must be designed in the context of the objectives of the program. For example, a monitoring program for an industry seeking to comply with monitoring requirements under its National Pollutant Discharge Elimination System (NPDES) permit may be relatively straight-forward, whereas more in-depth monitoring research related to factors affecting BMP performance will be more complex. Key principles include:

- Dedicate the time and resources to develop a sound monitoring plan. Complexities of plans will vary depending on monitoring objectives.

- Be sure to plan and budget for an adequate number of samples to enable proper data interpretation.

- Be aware of the many static and state variables that need to be documented as part of a monitoring program. Exhibit 1-4 provides a brief overview of some key variables.

- Be sure that the monitoring design properly identifies the relationship between storm characteristics and the design basis of the BMP. (For example, is the intent of the monitoring program to assess performance over all storm conditions or only design conditions? What types of storms are considered to be adequately representative for purposes of monitoring?)

- Properly implement and follow the monitoring plan, clearly documenting any adjustments to the program. Particularly important are proper equipment installation and calibration, proper sample collection techniques and analysis, and maintenance of equipment for longer term programs.

- Expect the unexpected: rodents building nests in monitoring equipment, vandalism, battery/power failures, etc. Monitoring programs require attention and ongoing adjustment.

- Maintain data in an organized and well-documented manner, including not only monitoring data, but also BMP design and maintenance practices and site characteristics.

- Clearly report study limitations and other caveats on use of the data.

The remainder of this Manual provides detailed guidance on many of these issues.

Exhibit 1-4. Examples of Static and State Variables to Report in BMP Monitoring Programs (*See Appendix A for a complete list specified by BMP type in the BMP Database.*)

Example Static Variables	Example State Variables
Tributary watershed conditions:	Rainfall intensity
Geographical location	Storm Size
Watershed size and slope	Flow rate
Land use type and characteristics (e.g., curb/gutter, imperviousness)	Season
Vegetative canopy/condition (*may also be a state variable*)	Upstream non-structural controls
Soil types and condition	Inter-event timing
BMP design (e.g., length, width, height, storage volume, outlet design, upstream bypass, model number)	Settings for control structures such as gates, valves, and pumps
	Modifications to BMP design over time
	Maintenance of the BMP

1.5 The International Stormwater BMP Database

As noted earlier in this chapter, a primary driver for the development of this Manual is the BMP Database project, which began in 1996 with the long-term goal of gathering transferable technical design and performance information to improve BMP selection and design so that local stormwater problems can be effectively addressed. In 2004, the project transitioned from a USEPA funded grant project to a more broadly supported coalition of partners including the Water Environment Research Foundation (WERF), ASCE Environmental and Water Resources Institute (EWRI), Federal Highway Administration (FHWA) and the American Public Works Association (APWA). These entities continue to provide long-term support of the project. The cornerstones of the project are the BMP monitoring and reporting protocols and the BMP Database itself, which were developed based on the input and intensive review of many experts for the purpose of developing standardized reporting parameters necessary for more accurate BMP performance analysis. The database encompasses a broad range of parameters including test site location, watershed characteristics, climate data, BMP design and layout characteristics, monitoring instrumentation, and monitoring data for precipitation, flow and water quality.

The database is available for download from the project website (http://www.bmpdatabase.org) and has evolved from its original 1999 release on CD to a more flexible and user-friendly structure. The three key component of the BMP Database include:

1) Data Entry Spreadsheets: These are forms for use by researchers and data providers to track BMP monitoring data, both for their own purposes, as well as for submitting data to the BMP Database. These spreadsheets are consistent with the structure and

data elements contained in the original database release on CD, but allow more flexibility for database users in a familiar Excel format.

2) BMP Database: This is the master database itself, which is loaded with over 350 BMP studies and continues to grow through submission of studies from researchers and many entities regulated under the stormwater NPDES program.

3) BMP Performance Summaries: Data submitted to the database are analyzed on approximately an annual basis, with results reported in several different formats. Cumulative performance across BMP categories is provided in summary tables and brief reports, as well as in "flat file" spreadsheets containing a summary of analysis data. Additionally, BMP performance results for individual submitted studies in PDF format can be downloaded using the on-line search engine at http://www.bmpdatabase.org.

Following the guidance provided in this Manual should typically result in studies being compatible for inclusion in the BMP Database and facilitate progress towards the BMP Database project's long-term goals, both with regard to traditional stormwater BMPs and LID approaches.

1.6 Regulatory Environment

Although BMP monitoring is conducted for both regulatory and non-regulatory purposes, in many cases, it is driven by regulations, even if the regulation itself does not "require" monitoring. As general background for BMP monitoring, it is important to be aware of several key regulatory drivers related to BMP monitoring programs, including:

- The Clean Water Act (CWA) of 1972: Section 208 of 1972 CWA requires every state to establish effective BMPs to control nonpoint source pollution. The 1987 Water Quality Act (WQA) added Section 402(p) to the CWA, which requires that urban and industrial stormwater be controlled through the NPDES permit program. As a result, urban areas must meet requirements of Municipal Separate Storm Sewer System (MS4) permits, and many industries and institutions such as state departments of transportation must also meet NPDES stormwater permit requirements. Even if monitoring is not required under the NPDES permit, operators of regulated MS4s are required to develop a Stormwater Management Plan (SWMP) that includes measurable goals and to implement needed stormwater management controls (BMPs). MS4s are also required to assess controls and the effectiveness of their stormwater programs and reduce the discharge of pollutants to the "maximum extent practicable."

  Section 303(d) of WQA requires the states to list those water bodies that are not attaining water quality standards including designated uses and identify relative priorities among the impaired water bodies. States must also develop Total Maximum Daily Loads (TMDLs) to assign allowable pollutant loads to various sources to enable the waterbody to attain designated uses in the future. (For more information about the TMDL program, see http://www.epa.gov/owow/tmdl.) Implementation plans to achieve the loads specified under TMDLs commonly rely on BMPs to reduce pollutant loads associated with stormwater sources.

- Coastal Zone Act Reauthorization Amendments (CZARA) of 1990: CZARA was passed to help address nonpoint source pollution in coastal waters. Each state with an approved coastal zone management program must develop and submit to the USEPA and National Oceanic and Atmospheric Administration (NOAA) a Coastal Nonpoint Pollution Control Program (CNPCP), which provides for the implementation of the most economically achievable management measures and BMPs to control the addition of pollutants to coastal waters.

  CZARA does not specifically require that states monitor implementation of management measures and BMPs. They must, however, provide technical assistance to local governments and the public in the implementation of the management measures and BMPs, which may include assistance to predict and assess the effectiveness of such measures.

  CZARA also states that the EPA and NOAA shall provide technical assistance to the states in developing and implementing the CNPCP, including methods to predict and assess the effects of coastal land use management measures on coastal water quality and designated uses.

- The National Environmental Policy Act (NEPA): NEPA establishes judicially enforceable obligations that require all federal agencies to identify the environmental impacts of their planned activities. The NEPA legislation and its requirements provide the framework under which environmental impacts of all substantial federal projects are evaluated, and have been the starting point from which many other environmental regulations are applied and enforced. Any major effort that involves federal funding, oversight, or permits, such as highway operations and projects, is subject to the NEPA process to ensure environmental concerns are considered and documented in an Environmental Impact Statement (EIS) before implementation.

- The Endangered Species Act: The Endangered Species Act of 1973 protects animal and plant species currently in danger of extinction (endangered) and those that may become endangered in the foreseeable future (threatened). It provides for the conservation of ecosystems upon which threatened and endangered species of fish, wildlife, and plants depend, both through federal action and by encouraging the establishment of state programs.

- State, Regional and Local Regulations: Increasingly, state and local governments and regional agencies may also develop their own rules and regulations requiring BMPs to protect drinking water supplies, recreational values, aquatic life and other beneficial uses. In some cases, such regulations focus primarily on water quality; however, more recently, such ordinances also focus on volume reduction through implementation of LID strategies that seek to mimic pre-development hydrology.

Because regulations are continually evolving and may vary by location, it is always prudent to check with key federal, state, regional, and local sources for the most up-to-date regulatory requirements that could affect BMP monitoring programs.

1.7 Manual Scope Limitations

The audience for this Manual is targeted primarily to those who possess a basic level of knowledge regarding stormwater quality, hydrology, and regulatory issues. The EPA website (http://www.epa.gov) and other state and local websites can be referenced for additional guidance and background information.

This Manual focuses primarily on the collection, reporting, and analysis of water quantity and quality measurements at the heart of quantitative BMP efficiency projects. It does not address, in detail, sediment sampling methods and techniques, biological assessment, monitoring of receiving waters, monitoring of groundwater, streambank erosion, channel instability, channel morphology, or other activities that in many circumstances may be as, or more, useful for measuring and monitoring water quality for assessing BMP efficiency.

This Manual addresses methods that were in use at the time it was written. As the state of the practice and the design of monitoring equipment progress, new monitoring approaches and techniques, more sensitive devices, and equipment based on new technologies will likely be employed. Although the technology may change somewhat from that described herein, most of the basic flow and water quality monitoring methods discussed in this document have a long history of use and will most likely remain viable even as new and different technologies emerge.

Exhibit 1-5. Other Resources for More Information on Stormwater Monitoring

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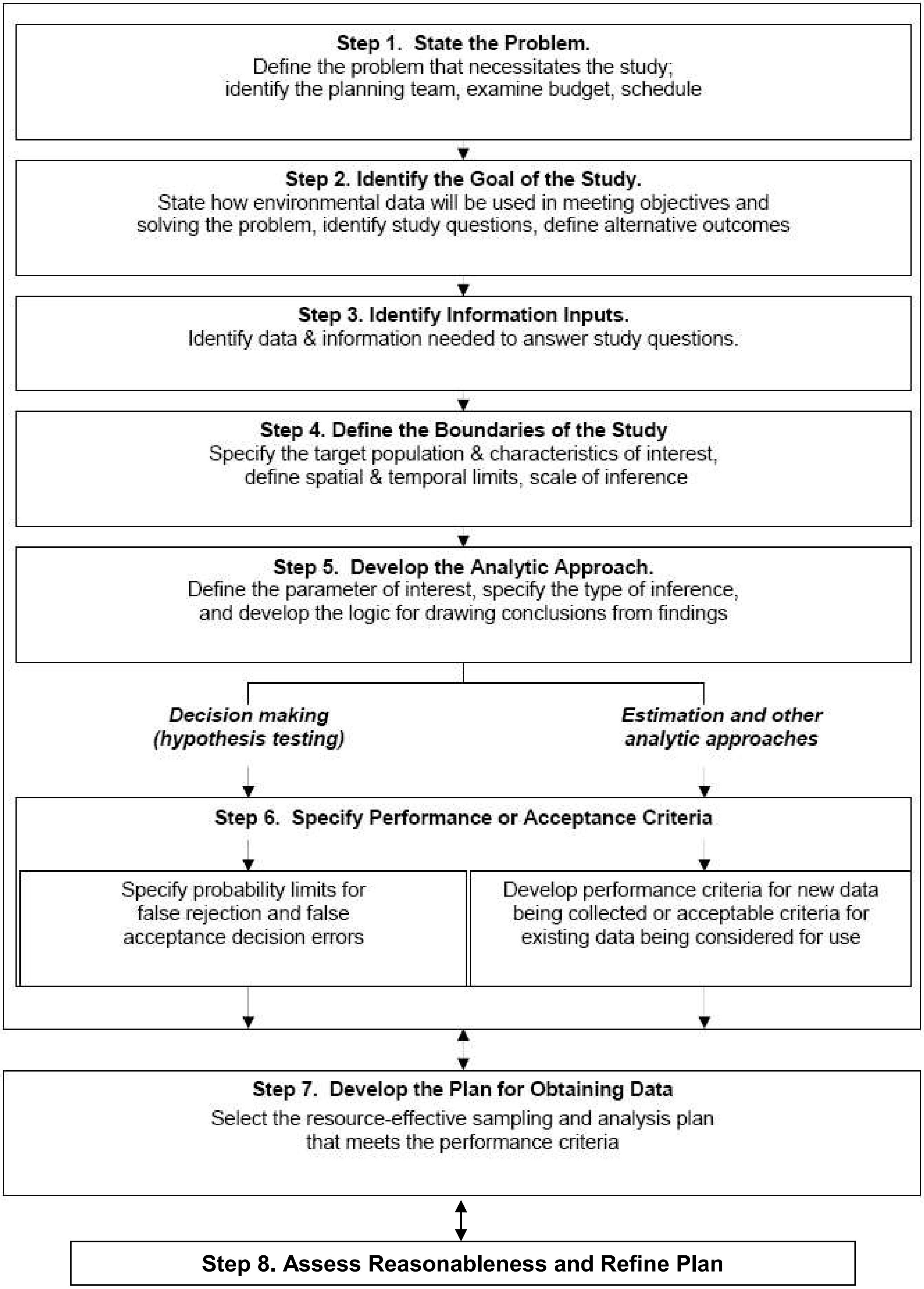
Chapter 2
DEVELOPING A MONITORING PLAN

This chapter provides a seven-step approach for developing a monitoring plan for collection of data to evaluate BMP effectiveness. The method described incorporates many elements that are included in EPA guidance regarding Data Quality Objectives (DQOs) (EPA 2006) and Quality Assurance Project Plans (QAPPs) (EPA 2002). Exhibit 2-1 provides a flow chart for working through these systematic steps, including the following:

1) Define Study Objectives
2) Identify Study Goals
3) Identify Information Inputs/Data Needs
4) Define Study Boundaries
5) Develop the Analytical Approach
6) Specify Performance or Acceptance Criteria
7) Develop Detailed Plan of Obtaining Data
8) Assess Reasonableness of Plan and Refine

This chapter describes representative considerations for each of these steps in the context of stormwater BMP monitoring.

Exhibit 2-1. Systematic Approach to BMP Monitoring Plan Development (EPA 2006)



2.1 Step 1. Define Study Objectives/State the Problem

It is very important that the objectives of a BMP monitoring program be clearly stated and recorded. The process of writing them down, working as a project team, generally results in careful consideration being given to the various possible objectives and questions to be answered. Written objectives help avoid misunderstandings by project participants, are an effective way of communicating with sponsors, and provide assurance that the monitoring program has been systematically planned.

Studies of BMP performance are usually conducted to obtain information regarding one or more of the following questions:

- What degree of pollution control or effluent quality does the BMP provide under normal conditions (i.e., representative storm types)?
- How does hydrology for developed conditions compare with pre-development hydrology in terms of peak flow rates, runoff volume, peak timing, site infiltration capacity, etc.?
- How does this performance vary from pollutant to pollutant?
- How does this normal performance vary with large or small storm events?
- How does this normal performance vary with rainfall intensity?
- How do BMP design variables affect performance?
- How does performance vary with different operational and/or maintenance approaches?
- Does performance improve, decay, or remain stable over time?
- Does performance vary seasonally? (For example, to what extent is infiltration reduced during cold temperatures?)
- How does this BMP's performance compare with the performance of other BMPs?
- Does this BMP help achieve compliance with water quality standards?

Many BMP monitoring programs have been established to satisfy requirements prescribed by permits to monitor the effectiveness of BMPs, but often the wording of such requirements is vague. Local program-specific objectives are likely to provide the soundest basis for planning a BMP monitoring study.

2.1.1 Key Activities for Step 1

Key activities for establishing monitoring objectives include the following:

1) Identify project team and identify decision makers, including project management/oversight, field staff, office staff, analytical technicians or laboratory, data users, project advisors, and peer reviewers.

2) Describe the problem and develop a conceptual model of the BMP to be investigated and identify general types of data that will be collected (i.e. hydrology, water quality, physical characteristics of facility). As part of this step, it is also important to understand and document basic site conditions affecting monitoring. For example, what is the source of the runoff (e.g., roofs, pavements) and where are the collection pipes? In general, what pollutants are anticipated from each source? For example, roof runoff may have copper from downspouts, pavement may have elevated chlorides from road salting in the winter, and lawns may have bacteria loading from geese or dogs. Are there unique soil conditions or karst topography?

   Exhibit 2-2 provides an example conceptual model of a bioretention cell and data that could potentially be collected including surface inflows; overflows/bypass; underdrain outflows; evapotranspiration; precipitation; infiltration to underlying water table; soil characteristics such as porosity, hydraulic conductivity, and pH; water quality constituent inflows, outflows, storage and bypass; and transport mechanisms including vegetative uptake, sorption/desorption, and advective transport. As Exhibit 2-2 illustrates, in many cases the conceptual model developed as a part of Step 1 will have many parameters, often more parameters than it will be feasible to measure.

Exhibit 2-2a. Conceptual Model for a Bioretention Cell with Underdrain (Source: Hunt 2003)
(*diagram terms defined in Exhibit 2-2b*)

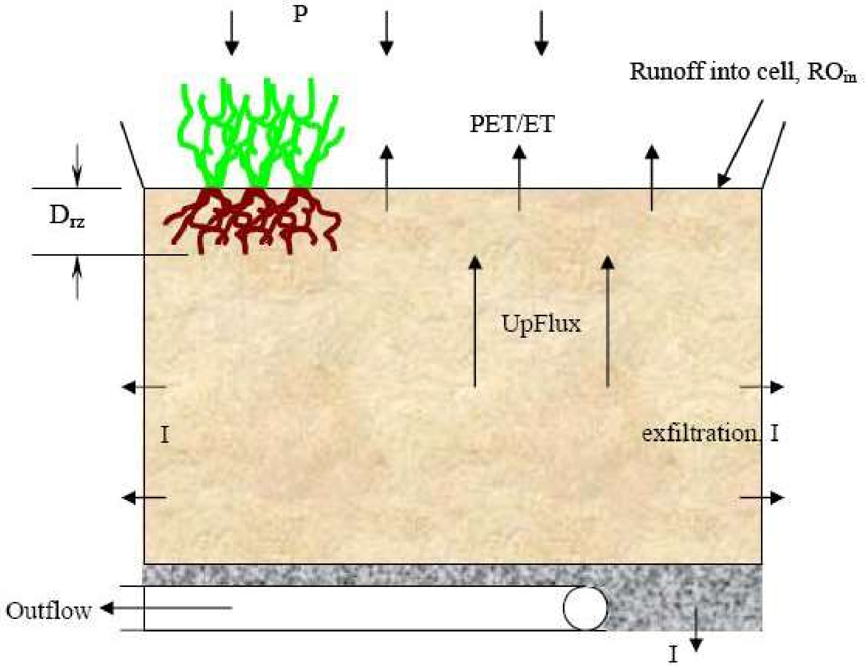
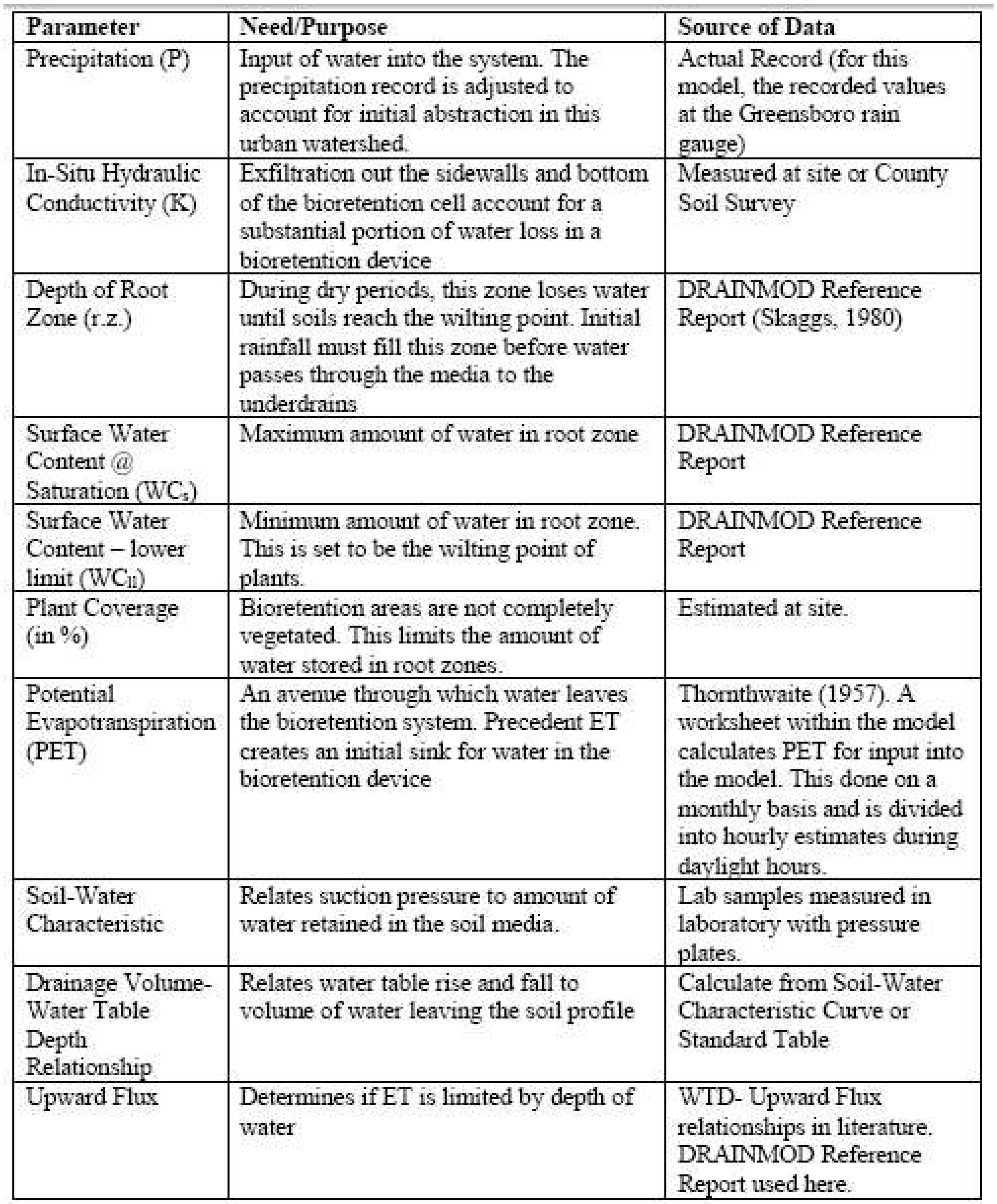


Exhibit 2-2b. Description of Conceptual Model Parameters (Source: Hunt 2003)



Parameter	Need/Purpose	Source of Data
Precipitation (P)	Input of water into the system. The precipitation record is adjusted to account for initial abstraction in this urban watershed.	Actual Record (for this model, the recorded values at the Greensboro rain gauge)
In-Situ Hydraulic Conductivity (K)	Exfiltration out the sidewalls and bottom of the bioretention cell account for a substantial portion of water loss in a bioretention device	Measured at site or County Soil Survey
Depth of Root Zone (r.z.)	During dry periods, this zone loses water until soils reach the wilting point. Initial rainfall must fill this zone before water passes through the media to the underdrains	DRAINMOD Reference Report (Skaggs, 1980)
Surface Water Content @ Saturation (WC_s)	Maximum amount of water in root zone	DRAINMOD Reference Report
Surface Water Content – lower limit (WC_{ll})	Minimum amount of water in root zone. This is set to be the wilting point of plants.	DRAINMOD Reference Report
Plant Coverage (in %)	Bioretention areas are not completely vegetated. This limits the amount of water stored in root zones.	Estimated at site.
Potential Evapotranspiration (PET)	An avenue through which water leaves the bioretention system. Precedent ET creates an initial sink for water in the bioretention device	Thornthwaite (1957). A worksheet within the model calculates PET for input into the model. This done on a monthly basis and is divided into hourly estimates during daylight hours.
Soil-Water Characteristic	Relates suction pressure to amount of water retained in the soil media.	Lab samples measured in laboratory with pressure plates.
Drainage Volume-Water Table Depth Relationship	Relates water table rise and fall to volume of water leaving the soil profile	Calculate from Soil-Water Characteristic Curve or Standard Table
Upward Flux	Determines if ET is limited by depth of water	WTD- Upward Flux relationships in literature. DRAINMOD Reference Report used here.

3) When a complex conceptual plan with many parameters is developed, it is necessary to make an assessment of the level of complexity of the monitoring that will be conducted. As a part of Step 1, parameters in the conceptual model can be prioritized into tiers that will aid in further steps to determine which parameters will be monitored, which ones will not be, and which ones will be estimated or calculated.

4) Discuss and evaluate alternative approaches to evaluating problem. Can goals be accomplished by evaluating data that have already been collected for other projects? If additional data are collected, can they be complemented by already-collected data? Because of the typically high cost of BMP monitoring, it may be desirable to evaluate alternative means for addressing some information needs (assuming that BMP monitoring

is not required to comply with a permit). Depending on the situation, sediment sampling, biological sampling, and/or visual surveys of the stormwater conveyance system may be cost-effective alternatives to stormwater quality monitoring. Literature reviews may also help address some stormwater management issues.

5) Identify key resources, constraints, deadlines. Resources could include the number of candidate BMP sites for monitoring, availability and/or cost of monitoring equipment, availability of staff to assign to the project, technical expertise of staff, funding resources, partnership opportunities, etc. Constraints typically arise from physical factors, practical factors and lack of resources. Constraints can include practical ability to collect measurements/samples; achievable accuracy and precision of measurements; geographic proximity of monitoring site to laboratory and/or location of monitoring staff; wet-weather site access; sample collection and processing time; natural variability in stormwater runoff hydrology and water quality; financial limitations; and other factors such as the age of the facility (e.g., are conditions at a new facility adequately stabilized to represent expected normal site conditions?). Deadlines may arise for many reasons including permit compliance timelines, grant durations, seasonality or internal progress goals.

Typical information that should be collected as a part of assessing resources in Step 1 includes the following:

- Results from prior surface water and groundwater quality studies, other BMP monitoring studies in the local area, sediment quality studies, aquatic ecology surveys, dry weather reconnaissance, etc.
- Drainage system maps.
- Land use maps (or general plan or zoning maps).
- Aerial photographs.
- Precipitation and streamflow records.
- Reported spills and leaks.
- Interviews with public works staff.
- Literature on design of structural BMPs to understand functionality and pollutant removal processes.

For BMPs monitored in industrial areas, the following information may also be relevant:

- BMP performance data for similar industries in region.
- Facility map(s) showing locations of key activities or materials that could be exposed to stormwater.

- Lists of materials likely to be exposed to stormwater.
- Reported spills and leaks.
- Interviews with facility staff and others who are knowledgeable about the facility.

2.1.2 Outputs from Step 1

Primary outputs from this Step 1 include the following:

1) A concise written description of the problem to be investigated. This can later be incorporated into the QAPP directly.
2) A conceptual model of BMP operation and site conditions including key parameters for evaluation of BMP effectiveness. Representative practical considerations (i.e., “reality checks”) associated with this step that can influence the financial and scientific success of the project are summarized in Exhibit 2-3.
3) A roster and conceptual organization chart for the project team.
4) A summary of resources including estimated available budget, available staff, potential partnerships, key deadlines and preliminary schedule.

Exhibit 2-3. Representative Practical Considerations at the Project Planning Level (Source: Granato 2009)

Basic Meteorological Data:

- Expected number of storms/year—will it be possible to get an adequate sample set during the time frame of the study?
- Expected range of sampling rates based on anticipated range of volumes per storm—will it be possible to get enough flow at the inlet to measure the flow and enough sample volume for multiple analyses without constant adjustments in sampling rates?
- What range of storm volumes associated with which storms should be sampled?
- Are average storm durations and holding times for proposed analytes realistic? (For example, if transporting bacteria samples to a lab within a 4-6 hour holding time is an objective and the average storm duration is 18 hours, do you have the time and people to do this sampling?)

Basic Watershed Characterization ("reality check" parameters):

- Imperviousness of tributary area—what proportion of precipitation is realistically expected as runoff at the inlet?
- Land use—what range of concentrations and constituents are expected? For example, it may be helpful to develop a basic range of expected water quality results based on sources such as the National Stormwater Quality Database (http://unix.eng.ua.edu/~rpitt/Research/ms4/Paper/Mainms4paper.html) for estimates.

Basic Engineering Design Information

- Is the selected site representative of good design practice or is the selected BMP an "outlier"?
- What is the expected range of storm sizes that will cause bypass, overflow, or failure? If bypass or overflow is anticipated, has monitoring equipment been planned for those locations?
- What design aspects will affect monitoring design? For example, how long will the outflow discharge need to be monitored to obtain an outflow sample comparable to the runoff inflow?

2.2 Step 2. Identify Study Goals

The primary focus of Step 2 is to further define the overall study objective and problem statement into a series of more-detailed questions that can then be evaluated for decision making implications and evaluated to determine key measurements that must be collected. For simple evaluations, a study goal may be summarized in a single question. For more complex studies, typical of many BMP monitoring situations, multiple questions will be required to define study goals. Step 2 should further define the focus of Step 1 and specify additional details on data collection plans and the specificity of the question to be answered by the data. Examples of goals/questions formulated in Step 2 based on objectives formulated in Step 1 could include the following:

Example Step 1 Objective:

1) What degree of pollution control or effluent quality does a bioretention BMP provide under normal conditions?

Example Step 2 Goals/Questions:

1) For all storm events monitored, do water quality sampling results from inflows and outflows exhibit a normal distribution? Do they exhibit a log-normal distribution?

2) On an annual basis, what fraction of runoff bypasses the bioretention BMP?

3) What fraction of the annual load of total phosphorus bypasses the BMP on an annual basis?

4) For all storm events monitored, what are the measured differences in BMP surface inflows and outflows in terms of peak rate and runoff volume?

5) For storm events up to the BMP design storm, what are the measured differences in BMP surface inflows and outflows in terms of peak rate and runoff volume?

6) For total rainfall depths up to the 90th percentile storm, are inflow and outflow concentrations of total phosphorus statistically significantly different at a 95 percent confidence level?

7) How does the median underdrain outflow total phosphorus concentration from the bioretention BMP compare with the median runoff value from the National Stormwater Quality Database?

8) How does the median underdrain outflow total phosphorus concentration from the bioretention BMP compare with the median values in the inflow?

These are but a few of the many goals that could be specified to evaluate the degree of pollution control or effluent quality of a bioretention BMP under normal conditions. The number of questions that can be evaluated and project goals are typically limited by cost, staff, schedule, and the number of rainfall events that can reasonably be expected during the study period.

2.2.1 Key Activities for Step 2

Key activities for identifying and defining study goals include the following:

1) Identify principal study question or questions and evaluate responsive actions to various outcomes resulting from answering study questions. For some BMP effectiveness monitoring projects, there may not be a near-term direct response that is directly related to the data collected. Data may be submitted to the BMP Database and ultimately may contribute to decisions regarding BMP design criteria. On the other hand, some BMP effectiveness monitoring projects may lead to responsive actions based on results of monitoring, especially when permit compliance is concerned.

   For example, if a goal of a study is to assess whether a constructed wetland basin has effluent quality that is at or below the receiving water standards for dissolved copper, and results indicate that the pond effluent concentrations are higher than the standards, responses could include modifications to the pond outlet to increase residence time, consideration of alternate supplemental treatment, collection of additional data to tighten confidence intervals, etc.

2) Develop a decision statement or estimation statement based on potential outcomes or answering principal study question(s). EPA DQO guidance defines two primary types of problems that a monitoring study may seek to address: (1) decision problems and (2) estimation problems (EPA 2006). Decision problems generally are framed so that the results of the monitoring will result in an action, whereas estimation problems are often framed so that the results of the monitoring will provide additional information to more accurately describe the system and/or conceptual model. Examples of decision and estimation problems and statements for BMP effectiveness monitoring are provided in Examples A and B, respectively.

   Example A. Decision Problem/Principal Study Question

   - Does the mean annual nitrate concentration from an extended detention basin-constructed wetland treatment train exceed the agreed-upon concentration from the development agreement with the downstream homeowner's association for protection of lake water quality?

   Example A. Decision Statement/Alternative Actions

   - Concur that mean annual nitrate concentrations from the extended detention basin-constructed wetland treatment train meet the agreed upon concentration from the development agreement with the downstream homeowner's association for protection of lake water quality.
   - Analyze inflow nitrate data to look for unusually high values that could indicate source.
   - Survey homeowners on fertilization practices. Restrict fertilizer application.
   - Reevaluate maintenance schedule for constructed wetland to determine if BMP seasonally exports nitrate.

- Consider design modifications to pond or wetland basin.

Example B. Estimation Problem/Principal Study Question:

- Does the effluent quantity and quality for turbidity from a green roof improve as vegetation becomes better established?

Example B. Estimation Statement/Alternate Actions:

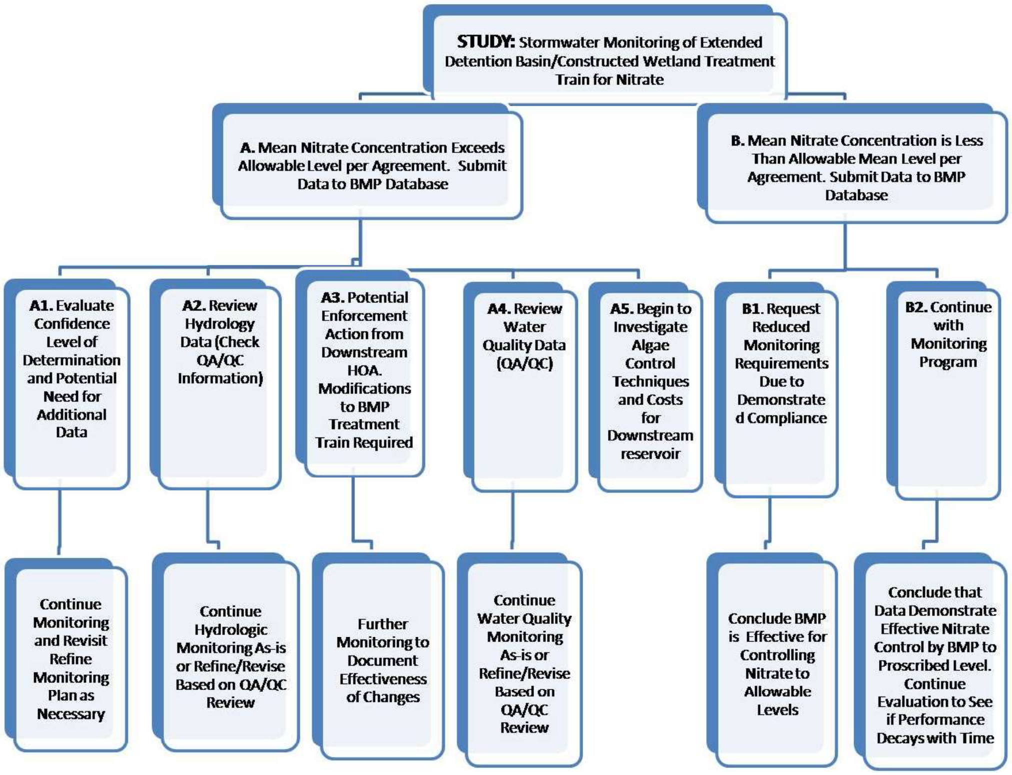
- Based on study from initial planting through three years of growth, runoff volume and turbidity levels both decline, indicating performance improves over time. Consider further evaluation of seasonal trends, effects of different types of vegetation, different types of soils, etc.

- Data from three year investigation show decrease in runoff volume but increase in turbidity levels. Evaluate hydrology/precipitation for trends, quantify extent of vegetative growth/exposed soil, consider further sampling/alternate sampling design to isolate source of turbidity.

- Study indicates that over three year study period, runoff volume and turbidity yields from the green roof increase. Evaluate hydrology/precipitation to see if increase runoff volume is due to greater precipitation, evaluate potential sources of turbidity.

Prioritize decision and/or estimation outcomes based on their relation to each other and relation to overall study goal. This task provides up-front planning regarding “what to do with the study results” under different scenarios. Using the decision-based example above, Exhibit 2-4 illustrates prioritization of outcomes. As shown in this example, two different series of actions result depending on the study results.

Exhibit 2-4. Example Prioritization of Outcomes and Response



2.2.2 Outputs from Step 2

Primary outputs from Step 2 include the following:

1) Well defined principal study questions. Questions should provide a refinement of the general study objective defined in Step 1 and provide detailed information that can be used in further steps to identify specific data to collect.

2) List of alternative outcomes resulting from answering study question. Anticipate conclusions that may be drawn from data collected and data analysis techniques employed.

3) Decision statement or estimation statement describing how findings of monitoring will be used to aid in decision-making and fulfill objective from Step 1.

2.3 Step 3. Identify Information Inputs

Step 3 identifies the specific type of information and data needed to address the overall study objective identified in Step 1 and the more detailed goals that have been developed as a part of Step 2. This step combines the conceptual model developed as a part of Step 1 with the specific questions of Step 2 to determine which components of the conceptual model will be measured, which will be estimated, and which may be available from existing technical literature. Constraints including available funding, equipment, technical expertise, practical considerations and capabilities for calculating or estimating various parameters from the conceptual model will shape the methods used to obtain the information inputs that the monitoring study seeks.

2.3.1 Key Activities for Step 3

Activities to identify information inputs (Step 3) include the following:

1) Determine types and potential sources of information needed. Potential sources of information can range from previously conducted studies to new data collection. Due to the high costs of data collection, garnering as much information as possible from past monitoring efforts located in the region or focused on similar BMPs can result in significant costs savings. Review of literature can provide comparable data, reveal problems encountered in similar monitoring efforts and troubleshooting solutions, and define criteria and measurement methods so that additional data collected will be comparable with past data collected.

   For data that are being collected that ultimately will be entered into the BMP Database, the data entry sheets from the BMP Database (http://www.bmpdatabase.org) can be a valuable resource for determining which facility characteristics, hydrologic and water quality parameters should be measured or estimated. Appendix A provides a copy of these forms.

2) Determine the basis for specifying performance or acceptance criteria for the collected data. Performance and acceptance criteria for data will vary with project objectives and goals and with the type of data collected (i.e., estimates from literature, reported values for measurements collected by others in relatively close proximity, direct measurements. Considerations may include the following:

   - Literature values: Considerations may include regional proximity to the study site, similarities in annual precipitation, similarities in BMP design criteria, similarities in land use, similarities in soil characteristics in the watershed and underlying the BMP, monitoring methods and quality assurance/quality control (QA/QC) protocols, ability to contact and communicate with the researchers who collected the data, and other factors.

   - Measurements collected by others (e.g., precipitation data collected at nearby weather station, stream gaging information, etc.): considerations may include the agency/entity collecting the data, proximity to the study site, precision and accuracy of the data, QA/QC protocols, temporal and spatial resolution of data, and similarities of environment in which data are collected and study environment.

   - Direct measurements: Considerations include precision and accuracy of monitoring equipment, method detection limits for analytical methods, sampling collection methods, allowable holding times, requirements for duplicate sampling and analysis and other QC checks (spikes, blanks, etc.).

   In addition to criteria for specific measurements, this step should also identify criteria for storm events that will be sampled. (See Section 2.3.2 for a more detailed discussion of this important topic.) These criteria include the number of storms to be monitored during the study; storm characteristics such as minimum or maximum precipitation depth, storm intensity, duration for inclusion in the study; antecedent dry time; and/or relationship of monitored storms to "typical" event (i.e., collect samples from storms with an event precipitation depth that is plus or minus one standard deviation from the mean annual storm depth for the area). In most cases, monitoring programs will focus on commonly occurring storms, typically serving as the basis of BMP design rather than large, in frequent storms. Although time and cost constraints may limit the ability to monitor infrequently occurring storm, data collected for infrequently occurring storms are often valuable for characterizing the limitations of BMPs. Even in large events, BMPs may provide treatment for the initial runoff from the event, providing water quality benefits. It also may be useful to document the dilution that can occur in larger events (for example, the quality of bypassed runoff in a larger event may be better than the treated portion, especially if remobilization of previously captured pollutants occurs within the BMP).

3) Verify the availability of appropriate sampling equipment and analysis methods. The project team should develop and review the list of desired measurements and specify how each measurement will be collected. This will typically involve

researching a variety of stormwater sampling products ranging from grab sampling equipment to automated sample collection equipment. For infiltration oriented practices, be aware that groundwater and/or vadose zone monitoring may be important components of the monitoring program, depending on study objectives. For any electronic equipment used, two very important considerations are the power source and communications capabilities (i.e., modem). This step will also involve contacting local laboratories to determine analytical methods that they may use for sample analysis, detection limits available for study parameters, and lab certification status. For constituents such as TSS and filtered metals that are subject to significant variability, it is important to thoroughly review and document lab procedures, even for certified labs following standard methods.

2.3.2 Determining Number of Storms Needed for Meaningful Statistical Assessment

2.3.2.1 General Considerations

The number of storms to be monitored each year (i.e., monitoring frequency) and the representativeness of the monitored storms with regard to study objectives are important considerations in planning the monitoring program. For example, a common LID study objective may be to evaluate performance of LID technique for small, frequently occurring storms, as opposed to large storms that exceed design parameters.

One of the most frequently overlooked factors in designing a monitoring plan is the number of samples required to obtain a statistically valid assessment of water quality. Budget and staff constraints generally limit the number of storms, locations, and parameters to be monitored. Program objectives should be weighed in light of available resources to determine the best mix of monitoring frequency, locations, and parameters. The cost of learning more (i.e., conducting more intensive monitoring) should be compared to the cost implications of moving forward too quickly and implementing extensive controls before having learned enough to guide planning, stormwater management commitments, and/or negotiations with regulatory agencies. The cost of controlling unimportant pollutants and/or unimportant sources, or implementing ineffective BMPs could easily exceed the cost of monitoring to learn more about actual BMP performance under the conditions that prevail in the system. Clearly, there is a need for balance here, because endless studies should not be substituted for control actions. In general, however, many measurements (i.e., many samples during many events) are necessary to obtain enough data to be confident of actual BMP performance, as opposed to drawing erroneous conclusions based on “noisy data” (e.g., variability artifacts caused by external factors, equipment and operator errors). Consequently, BMP effectiveness studies can be expensive and time-consuming.

Stormwater quality may vary dramatically from storm to storm. Therefore, monitoring a large number of storms is required if the objective of the program is to obtain accurate estimates of stormwater pollution in a given catchment (e.g., to determine whether water quality is changing over time or whether a given BMP is effective). However, staff and budget constraints typically limit monitoring to either a smaller set of parameters for many storms, or a more detailed monitoring approach including a larger set of parameters for a few storms. Often goals for a monitoring effort (e.g., to demonstrate that a specific BMP is achieving a given level of removal of a constituent) may not be consistent with fiscal limitations of the project.

Four factors influence the probability of identifying a significant temporal and/or spatial change in water quality:

1) Overall variability in the water quality data.
2) Minimum detectable change in water quality (difference in mean concentration).
3) Number of samples collected.
4) Characteristics of storms sampled (e.g., do the samples focus on frequently occurring events, or a wide range of storm conditions).
5) Desired confidence level from which to draw conclusions.

Estimates of the number of samples required to yield statistically valid monitoring results are necessary for making decisions about the nature and extent of monitoring efforts prior to implementation. Statistical analysis may be conducted to estimate how many events need to be monitored to achieve a desired confidence in a conclusion (i.e., power analysis). Performing a power analysis requires that the magnitude of detectable change, the confidence level, and the statistical power or probability of detecting a difference are defined. Typically, the confidence level and power are at least 95 percent and 80 percent, respectively, meaning that there is a 5 percent probability of drawing an incorrect conclusion from the analysis and a 20 percent probability that a significant change will be overlooked.

2.3.2.2 Sampling Strategies and Determination of Number of Samples for Paired Evaluations[1]

The comparison of paired data sets is commonly used when evaluating the differences between two situations (locations, times, practices, etc.). One common situation is the collection of paired influent and effluent samples from a control device being evaluated. However, it is critical to ensure that the samples being collected are truly “pairs.” The following discussion presents a range of sampling situations where paired analyses may be desired.

When monitoring very “small” control devices (those that have a short hydraulic detention time within the device), it is possible to take paired samples on a real-time basis. This would be possible for a flow-thru screen, for example, where there is no storage in the device. In this example, instantaneous pairs of influent and effluent samples can be taken because the same water is represented in both samples.

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[1] Guidance in this section taken directly from “Effort for Paired Samples.” Unpublished text prepared by Robert Pitt, P.E., Ph.D., University of Alabama, March 2009.

For somewhat "larger" devices (such as catchbasins with sumps, or an inlet insert placed in a catchbasin sump), the hydraulic residence time can be calculated using the discharge rate and the storage volume, as shown below:

Sump storage volume: 52 cubic feet
Discharge rate: 120 gal/min (= 16 ft^3/min = 0.27 ft^3/sec)

Residence time = 52 ft^3/16 ft^3/min = 3.3 minutes

Therefore, the flow would have to be reasonably steady for at a time substantially longer than this residence period, as this would likely be a completely mixed system and a plug flow system. Therefore, several residence time periods would be needed before approximate steady state conditions are attained. During this longer period, the influent may be rapidly changing (such as during summer thunderstorms), while the effluent will be slightly moderated by the storage in the system. A paired sampling scheme under this scenario could be comprised of many subsamples taken over a moderate period of time (several detention periods), such as 10 to 30 minutes, and composited for single influent and effluent analyses. Therefore, a single inlet and outlet sample would be a single pair, and each would be comprised of many composited subsamples taken over several residence time periods. In this case, an example could involve manual dipper samples every 30 to 60 seconds for a 30 minute sampling period.

A similar scenario would include a grass swale where the travel time along the test reach may be several minutes. However, in this case, plug flow would be more likely than completely mixed flow. Paired samples can also be composited over several travel time increments between the sampling locations, but it would also be a good idea to delay the start of the effluent samples by the expected travel time.

For even larger devices where the residence time is longer, such as in a bioretention device where the water may be in the device for many minutes to a few hours (assuming a small amount of ponding followed by filtering through soil media and then collected in an underdrain), composite samples should be taken during the complete period of flow at the influent and effluent (underdrain and overflow bypass) for each event. Therefore, each event would result in a single pair of samples.

For stormwater control devices that may contain water for extended periods, such as a wet detention pond or a wetland, the effluent during a rain event may be quite un-related to the influent water. During small rains, the total event runoff volume may be much smaller than the storage volume of the device. In this case, the effluent may be mostly "historical" water that has resided in the control device for some time. For very large rains, the runoff volume may be several times the storage volume of the device, and the effect of the "dilution" of the stored resident water would be less problematic. Therefore, paired sampling for these devices is much more complicated. Single event pairs are possible when the runoff volume is large compared to the storage volume. It is a good idea to calculate this "flushing ratio" for the events before analyzing the data. In this case, the best approach may be to examine the sum-of-loads for a season, where most of the influent and effluent during an extended period have been represented. Within this season, periodic large events can be evaluated as pairs, if the flushing ratio is large. It is important that all sizes of events be included in a sampling program, as small events are of interest when evaluating permit limits for heavy metals and bacteria, for example. Performance as a function of storm event size (flushing ratio) is also important and can be directly determined.

The number of influent/effluent sample pairs needed can be calculated based on the data quality objectives of the study, in a similar way that experimental design sampling efforts for characterization can be determined. Once the confidence and power of the desired outcome is known, it is possible to determine the sampling effort to identify a specific difference in influent and effluent concentrations. If only large differences need to be identified, then fewer samples are needed. However, if lower levels of performance need to be quantified, then more samples are needed. This “detection limit” of performance needs to be identified for the experimental design effort. Most statistical analyses determine if the influent and effluent are significantly “different.” However, many misinterpret the results if the samples are not statistically different by saying that they are the “same.” The correct interpretation is that there were not enough samples taken to show that they were significantly different. It is theoretically possible to statistically show that any paired set of samples are different if enough samples are taken. Of course, economics and opportunities limit the sampling effort. However, it is possible to identify the expected limit that any experimental design can detect as part of the sampling.

An equation (similar to the one used for single point characterization) that can be used to estimate the needed numbers of samples for a paired comparison (Cameron, undated; Burton and Pitt 2001) is as follows:

$$n = 2\,[(Z_{1-\alpha} + Z_{1-\beta})/(\mu_1 - \mu_2)]^2\sigma^2$$

where:

n = number of sample pairs needed

α = false positive rate (1-α is the degree of confidence. A value of α of 0.05 is usually considered statistically significant, corresponding to a 1-α degree of confidence of 0.95, or 95%)

β = false negative rate (1-β is the power. If used, a value of β of 0.2 is common, but it is frequently ignored, corresponding to a β of 0.5.)

$Z_{1-\alpha}$ = Z score (associated with area under normal curve) corresponding to 1-α

$Z_{1-\beta}$ = Z score corresponding to 1-β value

μ_1 = mean of data set one

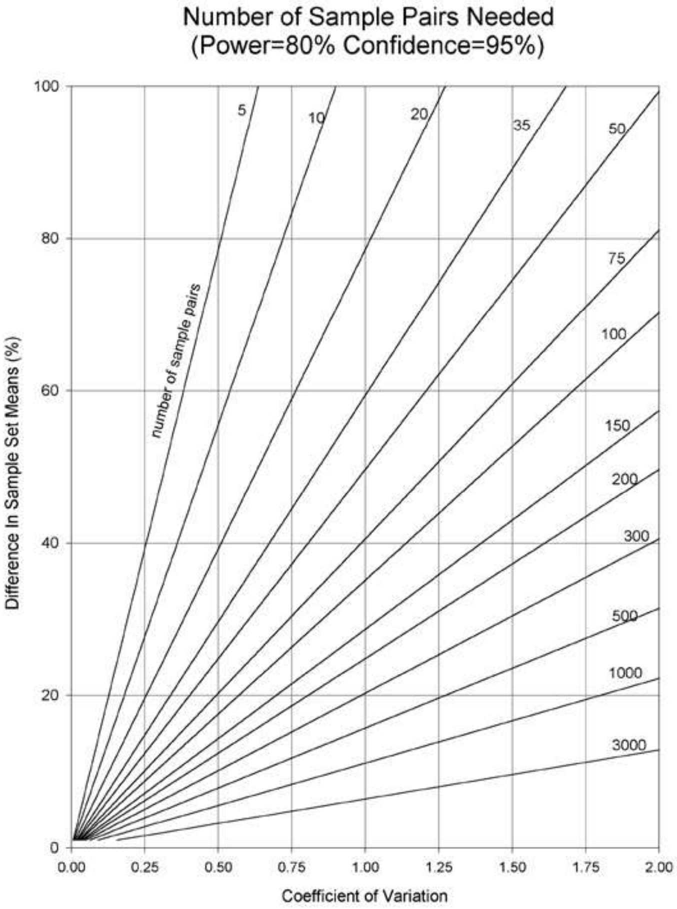
μ_2 = mean of data set two

σ = standard deviation (same for both data sets, same units as μ. Both data sets are also assumed to be normally distributed.)

This equation assumes that the two data sets be normally distributed and have the same standard deviations. Most stormwater parameters of interest are likely closer to being log-normally distributed. If the coefficient of variation (COV) values are low (less than about 0.4), then there is probably no real difference in the predicted sampling effort. This method should be used using log-transformed data for the more likely expected higher COV conditions.

Exhibit 2-5 (Pitt and Parmer 1995) is a plot of this equation (normalized using COV and differences of sample means) showing the approximate number of sample pairs needed for a typical value of α of 0.05 (degree of confidence of 95%), and a β of 0.2 (power of 80%). As an example, twelve sample pairs will be sufficient to detect significant differences (with at least a 50% difference in the parameter value) for two locations, if the coefficient of variations are no more than about 0.5. Appendix D (Pitt and Parmer 1995 and Burton and Pitt 2001) contains similar plots for many combinations of other levels of power, confidence and expected differences. References such as the BMP Database (http://www.bmpdatabase.org) and the National Stormwater Quality Database (http://rpitt.eng.ua.edu/Research/ms4/Paper/Mainms4paper.html) can be referenced for representative COVs when using Exhibit 2-5.

Exhibit 2-5. Sample Effort Needed for Paired Testing at a Power of 80% and Confidence of 95% (Pitt and Parmer 1995; Burton and Pitt 2001)



2.3.3 Outputs from Step 3

Primary outputs from the identification of information needs process (Step 3) include:

1) List of environmental characteristics, measurements and estimates that will provide answers to questions formulated for study goals from Step 2 and overall study objective from Step 1. For example, in a side-by-side small watershed comparison where one site has extensive rain gardens and the other does not, environmental characteristics, measurements and estimates could include the following:

    - Watershed area (each watershed).
    - Watershed imperviousness and land uses (each watershed).
    - Area of rain gardens in watershed.

- Design characteristics of rain gardens (hydrologic and hydraulic sizing, soils, vegetation, underdrains/no underdrains, etc.).
- Stormwater runoff hydrographs at primary storm sewer outfalls from each watershed at 5-minute intervals.
- Precipitation data (5-minute intervals) from tipping bucket rain gages in the watersheds.
- Flow-weighted composite water quality samples from each outfall for all events producing measurable runoff that can be sampled (acknowledging that there will be some events where staff errors or equipment malfunction will result in missed samples).
- Chemical analysis by qualified laboratory for total phosphorus, total suspended solids and chemical oxygen demand. (The laboratory selected could be a certified commercial laboratory or a well qualified research laboratory reporting complete QA/QC information.)

2) Information on the number of variables that will need to be evaluated and measurements collected. Depending on the objectives and goals of the study and the statistical confidence desired (as discussed in Section 2.3.2), the project team can identify the number of measurements desired. Due to both human and equipment errors and the extreme variability of stormwater runoff events, it is good practice to plan on collecting samples from 10 to 20 percent more events than are indicated from statistical analysis of data needs. By planning for these additional events, budget problems can be minimized due to "missed" events and progress expectations will be more reasonable.

3) Type and quality of information that will be needed to meet data performance or acceptance criteria. This will include a listing of the required measurement accuracy, method detection limits for analytical methods, and temporal and spatial resolution of data. It is noteworthy that detection limits achievable for research purposes may be lower than those available in commercial laboratories. In addition, available detection limits may vary from laboratory to laboratory (and even within a given lab, depending on cost). Therefore, selection of analytical methods and acceptable detection limits should take into consideration receiving water quality standards and other study objectives.

4) Identification of appropriate sampling and analysis methods. For a stormwater BMP effectiveness monitoring program, there are many alternatives for sampling and analysis that should be specified in this step including the following:

   - Manual sampling versus automatic sampling.
   - Grab sampling versus composite sampling (flow-weighted, time-proportional, random).

- Precipitation measurement (tipping bucket gage, total precipitation gage, nearby weather station).

- Flow measurement methods and equipment.

- Types of sample containers (and collection tubing) for various parameters.

- Definition of storm events (e.g., 6-hour separation or required antecedent dry condition). It may be useful to specify an antecedent dry period (i.e., 72 hours), as well as preceding/proceeding rainfall amounts. For example, it may not be useful to analyze samples from a 0.10-inch event occurring three days after a 0.5-inch event, but it could be useful to analyze samples from a 0.5-inch event within 24 hours of a 0.1-inch event. (Note: Some researchers prefer to sample all events so that a more complete population of sample conditions is represented; however, to accommodate a greater number of analyzed storms, it may be necessary to make economic tradeoffs with the number of parameters tested for some storms.)

- Allowable holding times.

- Handling requirements including field filtration, sample preservation, and temperature control.

- Field measurements such as pH, dissolved oxygen, oxidation-reduction potential, temperature, conductivity.

- Laboratory analyses and detection limits. Often there will be multiple methods for a given parameter with different detection limits and potentially different sample handling and preservation requirements. The method selected should have a detection limit that is consistent with the study goals and objective.

2.4 Step 4. Define the Boundaries of the Study

2.4.1 Key Activities for Step 4

Key activities for Step 4 include the following:

1) Define the target population of interest and relevant spatial boundaries. For stormwater BMP effectiveness monitoring, the target populations will generally include site/facility characteristics, hydrologic parameters and water quality parameters. The spatial boundaries of BMP monitoring efforts are critically important, especially for monitoring efforts where a mass balance estimate is desired for the BMP. Practical considerations in defining spatial boundaries of a monitoring study or evaluating a site to determine if it exhibits spatial boundaries that are likely to yield useful data include:

- The storm drain system should be sufficiently well understood to allow a reliable delineation and description of the catchment area (e.g., geographic extent, topography, land uses).

- For monitoring stations that will be used to measure flow in open channels, the flow measurement facilities need to be located where there is suitable hydraulic control so that reliable rating curves (i.e., stage-discharge relationships) can be developed. In other words, the upstream and downstream conditions must meet the assumptions on which the measurement method is based.

- Where possible, stations should be located in reaches of a conveyance where flows tend to be relatively "stable" and "uniform" for some distance upstream (approximately 6 channel widths or 12 pipe diameters), to better approach "uniform" flow conditions. Thus, avoid steep slopes, pipe diameter changes, junctions, and areas of irregular channel shape due to breaks, repairs, roots, debris, etc.

- Achieving well mixed conditions at a sampling station is an important consideration. In some cases, it may be advantageous to construct a “sampling box” to create cascading flow to the sample intake, thereby improving mixing.

- Locations likely to be affected by backwater and tidal conditions should be avoided since these factors can complicate the reliable measurement of flow and the interpretation of data.

- Stations in pipes, culverts, or tunnels should be located to avoid surcharging (pressure flow) over the normal range of precipitation.

- Stations should be located sufficiently downstream from inflows to the drainage system to better achieve well-mixed conditions across the channel and to favor the likelihood of "uniform" flow conditions.

- Stations should be located where field personnel can be as safe as possible (i.e., where surface visibility is good and traffic hazards are minimal, and where monitoring personnel are unlikely to be exposed to explosive or toxic atmospheres).

- Stations should be located where access and security are good, and vandalism of sampling equipment is unlikely. In some cases, it will be necessary to secure sampling equipment in protective boxes to guard against vandalism.

- Stations should be located where the channel or storm drain is soundly constructed. If a BMP is being installed and monitored for regulatory purposes, incorporating sampling needs into the BMP design can be cost-effective, as opposed to trying to retrofit the sampling equipment to the BMP later.

- If an automated sampler with a peristaltic pump is to be used, and the access point is a manhole, the water surface elevation should not be excessively deep (i.e., it should be less than 6 meters, or 20 feet, below the elevation of the pump in the sampler, and preferably less than 4.5 meters or 15 feet deep).

- If automated equipment is to be used, the site configuration should be such that confined space entry (for equipment installation, routine servicing, and operation) can be performed safely and in compliance with applicable regulations.

Prior to making a final determination on sample locations, each potential sampling station should be visited, preferably during or after a storm to observe the discharge. A wet-weather visit can provide valuable information regarding logistical constraints that may not be readily apparent during dry weather. Photo documentation of these conditions can be very helpful during implementation of the monitoring program. The importance of knowing the site cannot be overstated. This also includes being aware of factors influencing the site such as french drains, illicit discharges and maintenance practices such as street sweeping and power washing.

2) Define what constitutes a sampling unit. A sampling unit typically consists of a specified volume of an environmental media (water or soil) collected for analysis. The volume will be dictated by the volume requirements of the analytical methods used. For BMP effectiveness monitoring programs, sampling units could range from a series of discrete samples, to a flow-weighted composite sample. When considering what constitutes a sampling unit, it may also be useful to specify what constitutes a "complete" sampling event for a site. It is common to have multiple inflows to a BMP, and situations where some sampling stations function properly for sample collection and others malfunction should be anticipated. For example, to have a "complete" sampling event, is it necessary that all sampling stations at the site collect samples? Alternatively, would it be acceptable to count an event as "complete" if two of three inflow samplers trigger and collect samples along with the outflow? Answering these types of questions upfront is important because the cost of laboratory analysis can be significant and analysis of samples from storm events that do not meet criteria for being "completely" monitored may not be worthwhile to analyze in some cases.

3) Specify temporal boundaries and practical constraints associated with sample/data collection. Temporal boundaries include the start date of the BMP monitoring effort, the duration of the monitoring program, antecedent dry time required before samples are collected (typically 72 hours—but also dependent on the preceding amount of rainfall and intensity/washoff potential), frequency of sample or sub-sample collection during an event, allowable sample holding times, and targeted storm durations for monitoring. Temporal constraints may include access restrictions to a monitoring location during non-daylight hours, operating hours of laboratories, and staff working hours. From a practical standpoint, sampling may not be feasible on weekends, and analysis for some samples with

short hold times may not be practical for events sampled late on Fridays if laboratories are closed on weekends.

4) Specify the smallest unit on which decisions or estimates will be made. For BMP projects seeking to compare inflow and outflow water quality, the smallest unit for decision making is often whether or not there is a statistically significant difference between inflow and outflow mean or median concentrations at a given level of significance. For other monitoring efforts, it may be desirable to determine if a reduction in concentrations or mass is greater than or equal to a specific value.

2.4.2 Outputs from Step 4

Step 4 outputs include:

1) Definition of target populations and description of project spatial boundaries. This should include a site map and facility map showing relative physical characteristics related to the tributary watershed and the BMP. Sampling locations should be specified and parameters for each sampling/measurement location identified.

2) Definition of sampling unit. For water quality parameters, a table or list should be assembled with minimum sample volume requirements for laboratory analyses. Sample volume requirements to satisfy QA/QC requirements for replicate analysis, splits, spikes, etc. should also be considered to determine the sample volume required. A "go/no-go" rule should be developed for guidance when storms are partially sampled (i.e., not all stations function as intended, resulting in missed samples).

3) Data collection timeframe, temporal characteristics of monitoring plan and practical constraints. Allowing a reasonable time allotment for preparing a QAPP, a start date for monitoring should be established. The duration of monitoring should be established and constraints on the ability to collect or analyze samples should be identified (i.e., non-daylight hours, weekends, and/or holidays).

4) Scale for decision making or estimation. Based on the questions developed in Step 2, methods for analysis of data should be identified and levels of rejection or acceptance should be established. For statistical testing methods, this will involve specifying the mean hypothesized difference, statistical significance level and potentially other inputs to statistical methods.

2.5 Step 5. Develop the Analytical Approach

This step establishes how data that are collected will be analyzed to provide answers to the questions formulated in Step 2. This step should involve specification of relevant population parameters for analysis and statistical method that will be applied.

2.5.1 Key Activities for Step 5

Key activities for Step 5 include the following:

1) Specify appropriate population parameters for making decisions or estimates. Population parameters for decisions and estimates will be driven by the goals developed in Step 2. For many BMP effectiveness studies, the parameter of interest may be the mean or median EMC, reflecting representative performance of the BMP over the study period. Mean and median population values lend themselves well to statistical hypothesis testing. Other population parameters may be appropriate for other goals. For example, if the purpose of monitoring is for compliance with a discharge permit, the population parameter of interest could be the maximum measured concentration, the maximum EMC, a weekly or monthly average of measured parameters, etc. Exhibit 2-6 presents some of the more common population parameters for water quality monitoring.

2) For decision problems, choose an "action level" and generate "if…then…else" decision rule. Decision problems in BMP effectiveness monitoring usually arise from the need to meet a specified discharge concentration or loading rate or from the need to demonstrate a certain level of effectiveness. Typically "action levels" will arise from some form of regulation or agreement. For an example, an "action level" specified in a watershed management plan for a southeastern drinking water supply watershed is an allowable total phosphorus load of 0.20 lb/ac/year from development that occurs in the watershed. Residential developers in this watershed are required to adopt "conservation design" methods and LID BMPs and to conduct stormwater monitoring to demonstrate compliance with this loading criterion. In this case, an "action level" would be when data indicate that the annual loading of total phosphorus has exceeded 0.20 lb/ac/yr at an outfall from the development. An example of an "if…then…else" statement for this situation could be:

   > *If the annual total phosphorus loading at the outfall from the developed area is greater than 0.20 lb/ac/year, BMP maintenance and potential need for additional BMPs must be evaluated by the developer to reduce total phosphorus, else the total phosphorus loading from the development shall be deemed acceptable.*

3) For estimation problems, specify the estimator and estimation procedures. For assessment of BMP effectiveness, estimators may include population concentration and/or loading characteristics. For example, runoff flow measurements and flow-weighted composite samples could be used to estimate the mean concentration and annual loading of a pollutant in runoff from a specific land use. A mass balance is another example of an estimation problem, where estimators (based on flow and concentration data, typically) are loadings to and from the facility.

Exhibit 2-6. Examples of Population Parameters and Their Applicability to a Decision or Estimation Problem (Adapted from EPA 2006)

Parameter	Definition	Example of Use
Mean (arithmetic or geometric)	Average	Central tendency: Comparison of middle part of population to Action Level. Appropriate for chemicals that could cause cancer after a long-term chronic exposure. Use of the mean and the total amount of media (e.g., mass of soil or water) allows a planning team to estimate the total amount of a contaminant contained in the soil or water body. The arithmetic mean is greatly influenced by extremes in the contaminant distribution. Thus, for skewed distributions with long right tails, the geometric mean may be more relevant than the arithmetic mean. Neither may be useful, however, if a large proportion of values are below the detection limit. Although the arithmetic mean may not represent a good measure of central tendency in a skewed distribution, it remains an important statistic because the large values may represent the bulk of loads. For mass analysis, event mean concentrations (EMCs) from individual events can be flow-weighted based on event runoff volume to develop a flow-weighted average EMC for a series of events over a time period.
Median	Middle observation of distribution; 50th percentile; half of data is above and half is below	Better estimate of central tendency for a population that is highly skewed (nonsymmetrical). Also may be preferred if the population contains many values that are less than the measurement detection limit. The median is not a good choice if more than 50% of the population is less than the detection limit because a true median does not exist in this case (e.g., it would be reported as less than the detection limit). The median is not influenced by the extremes of the contaminant distribution.
Percentile	Specifies percent of sample that is below the given value; e.g., the 80th percentile should be chosen if you are interested in the value that is greater than 80% of the population.	For cases where only a small portion of the population can be allowed to exceed the Action Level. Sometimes selected if the decision rule is being developed for a chemical that can cause acute health effects. Also useful when a large part of the population contains values less than the detection limit. Often requires larger sample sizes than mean or median.

2.5.2 Outputs from Step 5

1) Identification of relevant population parameters.

2) “If…then…else” decision rule based on “action level” for decision problems.

3) Estimation method for estimation problems.

2.6 Step 6. Specify Performance or Acceptance Criteria

Performance and acceptance criteria for BMP effectiveness studies must be specified to define the level of confidence in analysis. Depending on the type of analysis that will be performed (i.e., statistical hypothesis testing, calculations to estimate parameters of a data population).

2.6.1 Key Activities for Step 6

1) Establish criteria for hypothesis testing. Hypothesis testing involves developing a null hypothesis, or baseline condition and an alternate hypothesis, or alternative condition. As an example, the null hypotheses could be that the mean outflow EMC of total suspended solids is not statistically different from the mean inflow EMC. The alternative hypothesis would be that the total suspended solids mean EMCs are different. When testing these hypotheses, data are analyzed at a specified confidence level, and results are interpreted as to whether to accept or reject the null hypothesis. Statistical hypothesis testing has four possible outcomes, summarized in Exhibit 2-7.

Exhibit 2-7. Potential Outcomes of Statistical Hypothesis Testing (EPA 2006)

Decision You Make by Applying the Statistical Hypothesis Test to the Collected Data	**True Condition (Reality)**	
	Baseline Condition is True	Alternative Condition is True
Decide that the Baseline Condition is True	Correct Decision	***Decision Error (False Acceptance)***
Decide that the Alternative Condition is True	***Decision Error (False Rejection)***	Correct Decision

The purpose of this step is to set upper limits on probabilities of false rejection (Type I) and false acceptance (Type II) decision errors. The probability of a false rejection decision is typically referred to as alpha (α) and is the test's level of significance. The probability of a false acceptance decision is called beta (β). The statistical power of a hypothesis represents the probability of a "true rejection" decision and is equal to $1-\beta$. Criteria should be established for both α and β as a part of this step. Figures showing the relationship between α, β, the magnitude of difference being tested and the number of samples are provided in Appendix C and may be useful for determining reasonable α and β values to use given the sampling and budget resources of the monitoring effort. More detailed discussion of hypothesis testing is provided in Chapter 7.

2) Establish criteria for estimates calculated based on data. For parameters that are estimated based on data collected (for example, mean total phosphorus EMCs in BMP inflows and outflows), it is necessary to quantify the uncertainty of the

estimate. The bias and precision associated with data collected directly impact the level of uncertainty in parameter estimates. Bias and precision (collectively known as accuracy) are two principal attributes of data quality in environmental studies. Bias represents systematic error (i.e., persistent distortion that causes constant errors in a particular direction), while precision represents random error (i.e., error among repeated measures of the same property under identical conditions, but not systematically in the same direction or of the same magnitude) (EPA 2006). Useful techniques for quantifying uncertainty include the following:

- Standard Errors: The standard error depends on factors that include the amount of data available, the underlying distribution, and the variability in the data used to calculate the parameter estimate. A standard error can be expressed in either absolute form (i.e., a single number that accompanies the estimate) or relative to the value of the parameter estimate (i.e., a proportion or percentage of the estimate). As an example of a relative standard error uncertainty criterion, a goal could be that the standard error not exceed 30 percent of the mean total phosphorus EMC estimate (EPA 2006).

- Confidence Intervals: A confidence interval is an interval used to estimate a population parameter from sample data. It is generally composed of two parts, an interval calculated from the data and a confidence level associated with the interval. The confidence interval is generally of the form: point estimate ± margin of error. The point estimate is a single value computed from the sample data (for example, a mean pollutant EMC concentration). To account for the possibility of estimation error, the margin of error is included in the confidence interval to provide a range of possible parameter values. The margin of error is what determines the width of the confidence interval (EPA 2006).

  In addition to the confidence interval, there is a confidence level associated with the interval. A confidence level gives the probability that the interval will capture the population parameter in repeated sampling. The level of confidence is expressed in terms of a percentage (e.g., 95 percent confidence). The larger the percentage, the more confidence that the interval contains the true value of the parameter. Consequently, the higher the confidence level, the wider the interval. Thus there is a trade-off between the confidence level and the interval width (EPA 2006).

- Tolerance Intervals: Tolerance intervals are similar to confidence intervals in that they portray uncertainty in a population parameter; however with tolerance intervals the parameter is a specified proportion of the population distribution. Specifically, tolerance intervals estimate the range that should contain a certain percentage of the values in the population. Similar to the concept of confidence level, researchers cannot be 100 percent confident that that interval will contain the specified proportion, only a certain percentage. There are two different inputs associated with the tolerance interval: a degree of confidence and a percent coverage. An example of tolerance interval could state 95 percent confidence that 90 percent of the population will fall within the range specified by the tolerance interval (EPA 2006).

- Prediction Intervals: While confidence and tolerance intervals estimate present population characteristics, the prediction interval estimates what future values will be, based upon previously collected data. Just as with confidence and tolerance intervals, prediction intervals incorporate the idea of a confidence level when attempting to determine what future values will be. For example, a goal could be to predict that the next set of samples will fall within a determined range with 99 percent confidence. To calculate prediction limits, estimates of the current population mean and standard deviation are needed. It is also necessary to decide how many sampling periods there will be and how many samples will be collected per sampling period. Once these factors are determined, a prediction interval can be calculated for estimating those future observations. Prediction intervals are always larger than confidence intervals (EPA 2006).

3) Identify conditions for site abandonment. In some cases, site conditions may either change over time or be misunderstood to an extent that the monitoring plan will not result in collection of data that are meaningful for the goals and objectives of the monitoring plan. Additionally, in some cases, a BMP being monitored may fail and no longer be viable for monitoring. For example, ultra clean sites may not yield useful information on the ability of the BMP to improve water quality and other sites may have problematic conditions such as backwater, abnormally high loading conditions, etc.

2.6.2 Outputs from Step 6

For studies that will involve hypothesis testing, the following outputs from Step 6 are necessary:

1) Well-formulated baseline condition statement (null hypothesis) and alternative conditions statement (alternative hypothesis).

2) Evaluation of consequences for false rejection and false acceptance decision errors.

3) Specified levels for α and β.

For studies involving estimation of a parameter from a population of data, outputs should include the following:

1) For a criterion using standard error, the desired maximum standard error, either as an absolute value or a percentage of the estimated parameter, should be specified.

2) For statistical intervals, values to specify include the confidence level that specifies the likelihood that the interval contains the true value of the parameter and the desired maximum width of the interval.

2.7 Step 7. Develop the Plan for Obtaining Data

After completing Steps 1 through 6, much of the information needed to develop a thorough and effective plan for collecting data is available. The objectives and goals have been established, types of measurements and estimates have been identified and criteria have been developed for performance or acceptance of results. The next step is to create a QAPP that describes the details of the sampling and analysis techniques that will be used. The sampling design in the QAPP should seek to maximize information that contributes to satisfying project goals within the budget and personnel constraints of the project. This section provides an overview of the elements of a QAPP. Very detailed guidance is available from EPA in the document *Guidance for Quality Assurance Project Plans* (EPA 2002).

2.7.1 Key Activities for Step 7

Key activities for Step 7 include the following:

1) Identify constraints affecting sampling and analysis design.
2) Describe in detail sampling and analyses that will be used.
3) Evaluate efficiency of sampling and analysis design.

The sampling and analysis design should be based on the DQOs developed through Steps 1 through 6 and the specific objectives and intended use of the data (hypothesis testing, estimation). Practical constraints should be considered in developing the QAPP.

2.7.2 Outputs from Step 7

The primary output from Step 7 is the QAPP. Key elements for a QAPP are categorized into these four groups (EPA 2006):

1) Group A – Project Management: These elements address project management, project history and objectives, and roles and responsibilities of the participants. These elements help ensure that project goals are clearly stated, that all participants understand the project goals and approach, and that the planning process is documented.

2) Group B – Data Generation and Acquisition: These elements cover all aspects of the project design and implementation (including the key parameters to be estimated, the number and type of samples expected, and a description of where, when, and how samples will be collected). They ensure that appropriate methods for sampling, analysis, data handling, and QC activities are employed and documented.

3) Group C – Assessment and Oversight: These elements address activities for assessing the effectiveness of project implementation and associated QA/QC requirements; they help to ensure that the QAPP is implemented as prescribed.

4) Group D – Data Validation and Usability: These elements address QA activities that occur after data collection or generation is complete; they help to ensure that data meet the specified criteria.

Exhibit 2-8 summarizes sections that should be included in the QAPP.

Exhibit 2-8. Elements of a QAPP (Source: EPA 2002)

Group A. Project Management	
A1 Title and Approval Sheet A2 Table of Contents A3 Distribution List A4 Project/Task Organization	A5 Problem Definition and Background A6 Project/Task Description A7 Quality Objectives and Criteria A8 Special Training/ Certifications A9 Documentation and Records
Group B. Data Generation and Acquisition	
B1 Sampling Process Design (Experimental Design) B2 Sampling Methods B3 Sample Handling and Custody B4 Analytical Methods B5 Quality Control	B6 Instrument/Equipment Testing, Inspection, and Maintenance B7 Instrument/Equipment Calibration and Frequency B8 Inspection/Acceptance of Supplies and Consumables B9 Non-direct Measurements B10 Data Management
Group C. Assessment and Oversight	
C1 Assessments and Response Actions	C2 Reports to Management
Group D. Data Validation and Usability	
D1 Data Review, Verification, and Validation D2 Verification and Validation Methods	D3 Reconciliation with User Requirements

2.8 Step 8. Assess Reasonableness of Plan and Refine

Once a monitoring plan (QAPP) has been developed, it is time to revisit the objectives and goals developed through the planning process to be sure that the plan will provide the data desired. Refinements to the plan at this step are common, and it is likely that even more refinements and changes to the plans will be required as implementation of the plan begins in the field and the laboratory and unforeseen practical constraints come into play.

2.8.1 Determine Project Costs and Funding Availability

One of the most important "reasonableness assessments" of a monitoring plan is to develop a detailed budget and compare it with available funding. Costs that must be accounted for include the following:

1) Equipment: Capital costs, installation costs, on-going maintenance, replacement parts, repair, etc.

2) Staff time: Field sampling, sample handling and transport, field trips for "false alarms" when samplers malfunction, coordination between team members and laboratory, data entry, data analysis, report writing (progress updates and final), photographic logs, cleaning equipment/bottles, troubleshooting, administrative support, etc.

3) Expenses: Mileage, copies, telephone, field supplies (waders, gloves, hardware, ice), specialized computer programs for data management/analysis, etc.

4) Laboratory/Analytical: Costs for analysis of samples collected for the suite of parameters, including samples needed for QA/QC such as field blanks and replicates. Commercial laboratories generally will provide price quotations if provided with the total number of samples and the desired parameters (be sure to be specific about desired methods and detection limits, which may be need to be lower than for typical laboratory analysis purposes).

5) Peer Review: It is often desirable to have a third party perform a peer review of monitoring data and interpretive reports to increase credibility of the data collected and conclusions.

6) Contingency: The QAPP should provide sufficient detail to develop a detailed cost estimate; however, given the uncertainty inherent in stormwater monitoring, a contingency should also be included in the budget estimate. For example, damage to equipment from animals, lightning and vandalism is not unusual.

2.8.2 Refine Plan Objectives Based on Budget Limitations

If the calculated budget is greater than the amount of funding available, it will either be necessary to narrow the scope of the monitoring project or obtain additional funding.

2.8.2.1 Prioritizing Goals and Data Collection Efforts

The first step to refining a monitoring plan to reduce the required budget is to revisit the overall objective from Step 1 and the goals developed as a part of Step 2. Representative questions to ask as a part of this assessment include:

- Is it possible to achieve the overall objective by addressing a subset of the questions/goals from Step 2?

- Do some of the goals have overlapping data collection requirements, making that data more "valuable" from the standpoint of addressing multiple goals?

- Are there some types of data that would render other types of data less useful if not collected (for example, if flow data are not collected, the utility of concentration data collected is diminished because a mass balance may not be reasonably calculated)?

- Can the list of parameters analyzed be reduced by using "surrogate" parameters as indicators? For example, could monitoring of total suspended solids effectiveness be used to infer, in a general sense, removal of particulate metals for a given pH range?

- Once monitoring has commenced, can the list of parameters analyzed be reduced based on laboratory results? For example, if dissolved cadmium is not detected at the specified detection limit over the first several storm events in inflows or outflows from a constructed wetland, can it be eliminated as a required parameter? Eliminating repeated analysis of samples that result in non-detects can result in significant budget savings during the implementation phase of a monitoring plan.

- Can some parameters be estimated rather than measured? This is a useful question to explore not only for prioritization of data collection efforts but also for filling in data "gaps" that result from missed samples, equipment malfunction, human error and a variety of other causes. (See Section 2.8.2.2 for a discussion of estimation techniques.)

- Is "breadth" or "depth" more important for the data that are being collected? There is an inverse relationship between the number of parameters that can be measured/tested for and the number of measurements for each parameter that can be collected. Often, sample size requirements to meet DQOs will restrict the number of parameters that can be tested under a given budget. If additional parameters are desired, it may be necessary to scale back the number of samples collected and relax acceptance and performance criteria. Alternatively, the list of parameters analyzed may be curtailed to maintain the desired performance and acceptance criteria.

2.8.2.2 Estimation of Parameters for Plan Refinement to Reduce Costs

When monitoring is constrained due to a limited budget or lack of sampling staff, estimates of water quality parameters, flow, and rainfall can be made using various models and assumptions. The use of modeling to estimate these parameters may limit usability of the data, depending on the validity of the assumptions made, the accuracy of the model itself, and accuracy of the information input into the model. Methods to estimate water quality, flow and rainfall parameters follow.

2.8.2.3 Estimates of Water Quality Parameters

Certain water quality parameters can be estimated by monitoring for related parameters that are simpler or less expensive. These related or surrogate parameters are statistically correlated to the more complicated or expensive parameters. Some common surrogate parameters and represented parameters are:

Surrogate Parameter	Parameter Represented by Surrogate
Turbidity	TSS
E. coli	Pathogens

Chemical Oxygen Demand (COD)	Biological Oxygen Demand (BOD)

In addition to monitoring for surrogate parameters at each monitoring site, water quality models can be used to estimate constituent concentrations at monitoring sites using available monitoring data, upstream land use, hydrology, geology, and history to calculate a mass balance for each constituent. Water quality models are a tool for simulating the movement of precipitation and pollutants from the ground surface through pipe and channel networks, storage treatment units, and finally to receiving waters. Both single-event and continuous simulation may be performed on catchments having storm sewers and natural drainage for prediction of flows, stages and pollutant concentrations. Each water quality model has its own unique purpose and simulation characteristics. It is advisable to thoroughly review downloading and data input instructions for each model.

The applicability and usefulness of these models is dependent upon a number of assumptions. The degree of accuracy of these assumptions determines the usefulness of the output data. For example, one assumption could be based on certain types of land use contributing certain constituents to the catchment runoff. The constituents associated with each land use have been well studied by many monitoring programs, but are still highly variable, depending on specific activities on each parcel, history of spills, age of infrastructure, climate, and many other factors. Although modeling of water quality parameters is a useful tool to estimate parameter concentrations, model results should not be interpreted as exact data. Confirmation of water quality model results should be done by monitoring a few storms and/or a few sites, then running the model with the observed conditions as input variables and comparing the results.

2.8.2.4 Estimates of Flow

Under certain conditions, flows entering and leaving a BMP can sometimes be modeled if actual monitoring is prohibitive. Most researchers strongly recommend against “taking shortcuts” in terms of flow monitoring; nonetheless, some basic techniques for estimating flow follow. Flow can be estimated at varying levels of detail using approaches ranging from simple spreadsheets to complex hydraulic simulations of extensive urban drainage networks. The simplest approach is to use the volumetric runoff coefficient approach, which is an empirical relationship that provides an estimate of total volume of runoff based on total volume of rainfall according to the following equation:

$$\text{Volume of Runoff} =$$

$$\text{Volume of Rainfall} \times \text{Volumetric Runoff Coefficient} - \text{Depression Storage}$$

This method is usually applied to smaller catchments such as parking lots, rather than entire watershed areas. Where monitoring data have been collected for some calibration period such that an accurate estimate of the volumetric runoff coefficient and depression storage for the watershed can be made, this approach coupled with accurate rainfall data may provide one of the least expensive methods for determining total volume of flow from a watershed on a storm-by-storm basis.

For studies where accurate flow data are fundamental to evaluation of performance of the BMP (i.e., many LID studies), flow estimation techniques are typically not an acceptable alternative to meet the study objectives in cases where flow monitoring is feasible.

2.8.2.5 Estimates of Rainfall

If a nearby rainfall gage is not available, rainfall at the monitoring site can sometimes be approximated using available gages that are located as close as possible and at similar elevation. A network of gages in an area can be analyzed to relate latitude, longitude, and elevation to rainfall. The grid of gages can be expanded and extrapolated to an area lacking any gages, provided that enough rainfall gages exist. This approach has significant limitations, particularly at small sites, and should be used only as a last resort

Because costs of rainfall monitoring equipment are often much less than other types of equipment and because rainfall patterns often vary significantly, it is highly recommended that rainfall monitoring be conducted instead of estimated. This is particularly true for LID-related studies were surface runoff volume reduction is a key measure of performance. Because of localized variability in storm conditions, sites with small tributary areas also generally require a rain gage at the site.

2.9 Conclusion

A systematically and carefully planned monitoring plan is essential to a cost-effective monitoring program that results in appropriate data needed to meet study objectives and goals. BMP monitoring is expensive and care should be taken to ensure that the study design will enable the researcher to draw statistically significant conclusions or meet other objectives such as permit requirements.

2.10 References

Note: This reference list include both publications cited in this chapter and additional resources that may be useful in developing a monitoring plan.

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Chapter 3
HYDROLOGIC AND HYDRAULIC MONITORING

The accurate collection and analysis of hydrologic and hydraulic data is one of the most important components of a Best Management Practice (BMP) monitoring study and is essential for Low Impact Development (LID) techniques and sites. To begin with, precipitation and other meteorological data are key components of watershed water balances needed to evaluate LID sites. Accurate flow measurements are also required to complete water balance computations and are critical for estimating BMP capture and bypass volumes, as well as volume losses. These flow rate measurements also affect the estimates of event mean concentrations (EMCs) and pollutant loads (see Chapter 4). **LID studies without well designed and implemented hydrologic and hydraulic monitoring components are of little value to the technical community.**

Hydrologic and hydraulic data can be collected using a variety of methods and equipment; the choice of which directly affects the usability of the data. This chapter discusses some of the methods and considerations for monitoring hydrologic and hydraulic phenomena and summarizes the equipment that can be used to collect data relevant to the evaluation of BMP performance. Additionally, practical considerations such as the critical importance of proper calibration of equipment and challenges associated with flow monitoring for LID studies are also discussed. For detailed discussion of water measurement practices, researchers are encouraged to see the U.S. Bureau of Reclamation (2001) *Water Measurement Manual*, which can be downloaded from http://www.usbr.gov/pmts/hydraulics_lab/pubs/wmm/, along with other references in Exhibit 3-1.

Exhibit 3-1. Supplemental Hydrologic Monitoring References

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3.1 Meteorological Data Collection

3.1.1 Precipitation

Precipitation monitoring is an essential component of any effective monitoring study. Precipitation data may help determine when to start sampling, as well as provide information to identify storm characteristics such as precipitation depth, duration, and intensities. Precipitation data are also important in terms of identifying when a storm begins and ends, which can be unclear in some climates. When combined with tributary area and land use characteristics, precipitation data can provide a “reality check” on flow data (e.g., was the reported flow physically possible for this storm event?). Accurate high resolution precipitation data are relatively inexpensive to collect, so the benefits of having such data typically outweigh the costs. Considerations related to the type and quantity of precipitation gages needed for study are identified below.

3.1.1.1 Types of Precipitation Gages

Standard Rain Gage

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.

Exhibit 3-2. Standard Rain Gage
(http://www.crh.noaa.gov/ind/?n=standardgage)

Tipping Bucket

A tipping bucket rain gage consists of a funnel that directs rainfall to one of two small "buckets." Once a given amount of rain falls into the funnel, usually 0.01 inches, a rocker mechanism empties the filled bucket and moves the empty bucket underneath the funnel. A recorder in the gage records each tip and the time in which the tip occurred. A tipping bucket gage may not be an effective option in some circumstances. For example, it cannot be used in freezing weather because the rocker mechanism can freeze and/or the funnel hole can become blocked with ice. The rocker mechanism may also fail or double tip during intense storm events. These devices can, however, be fitted with wind shields and antifreeze overflow devices. Additionally, precipitation can go undetected during extremely light and short events if the fixed amount of rainfall required to tip the bucket does not accumulate during the event. In all cases, rain intensity monitoring devices, such as that tipping bucket rain gage, need to have concurrent standard rain gage measurements to minimize these errors. In addition, they need to be calibrated at least twice a year. Tipping buckets can also be effectively used to trigger samplers (usually after about three tips to start the sampler; this is much more reliable than relying on flow alone to start the sampler in the presence of base flows).

Exhibit 3-3. Tipping Bucket Rain Gage
(http://www.arm.gov/instruments/instrument.php?id=rain)

Weighing Gage

A weighing precipitation gage collects precipitation data by directing precipitation into a container. 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 because it has an attachment that fits around the device to create a vacuum that reduces the effects of wind and allows the gage to catch more precipitation. 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 gages are more expensive and require more maintenance than tipping bucket gages.

Exhibit 3-4. Universal Weighing Rain Gage
(http://www.erh.noaa.gov/aly/COOP/Equipment/UWG.htm)

Optical Rain Gage

Optical rain gages are a relatively new technology compared to the standard, tipping bucket, and weighing rain gages described above. These gages measure precipitation by using a laser and phototransistor detector along with an array of collection funnels. When water falls into an optical rain gage, it passes through a laser beam and causes the beam to scatter. These light scatterings are then counted and recorded by the phototransistor detector and converted into rainfall measurements. As long as the collection funnels are heated to melt frozen precipitation, optical gages can operate in freezing conditions. On minute to minute and daily timescales, Ritsche et al. (2008) reported good agreement between tipping bucket and optical rain gages. Ritsche et al. also noted that on an annual basis, tipping bucket gages may underestimate precipitation due to mechanical limitations during periods of intense rainfall. Optical rain gages may overcome the types of mechanical issues associated with tipping buckets.

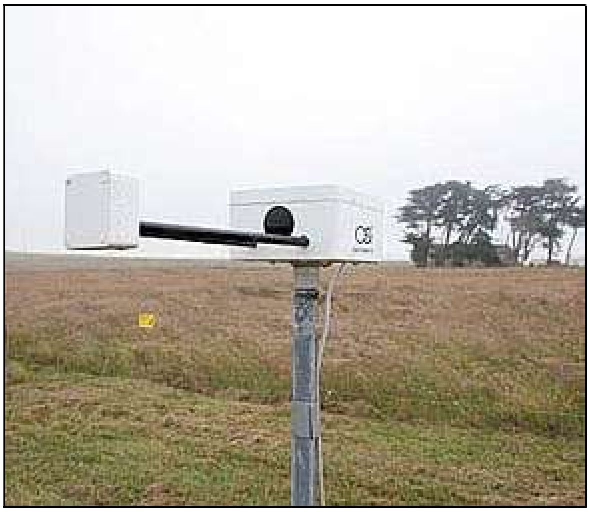

Exhibit 3-5. Optical Rain Gage

(http://www.arm.gov/instruments/instrument.php?id=org)

3.1.1.2 Site Proximity

In many regions, precipitation can vary significantly within a small geographic area because of orographic effects (i.e., weather effects of mountains), elevation, and proximity to water bodies. Therefore, it is important to position precipitation gages within or as close as possible to the drainage area tributary to the BMP. It may also be possible to use real-time data available over the Internet from rain gages operated by the U.S. Geological Survey (USGS), the National Weather Service, and/or the nearby municipalities. These established stations are convenient to use if they are in close proximity to the monitoring site, or as a general estimate of precipitation if they are located further from the monitoring site.

Precipitation gages typically need to be installed at the study site to obtain accurate precipitation data, unless another established gage is in adequately close proximity. Proper installation and maintenance of a rain gage is important and is relatively straightforward when manufacturers' guidelines are followed. The main concerns during installation are:

- Leveling the device.

- Making sure that vegetation (trees) or structures are not obstructing precipitation. A general rule of thumb is to place the device twice as far from the obstruction as the obstruction is tall.

- Providing enough height above the ground to prevent vandalism.

- Discouraging use as a perch by birds (e.g., install a bird wire).

- Being aware of possible influence of wind patterns around buildings in urban areas (e.g., make sure gage location conditions are comparable to area tributary to BMP).

- Positioning the rain gage in close proximity to other monitoring equipment to provide required connections for recording of precipitation depths and/or representative records.

3.1.1.3 Number of Gages

The number of precipitation gages installed in a study area directly affects the quality of storm event analyses and correlation of observed flow rates. Generally, more precipitation gages provide better estimates of precipitation characteristics. Locating a gage at each study site for small catchments is imperative because local variations in total precipitation and precipitation intensity can significantly impact the runoff for small watersheds. Nearby offsite locations (typically if over a mile away or at a different elevation) may not be useful in estimating precipitation at the actual site as a result of the variations which occur in precipitation over geographic areas.

In addition to the network of rain gages accessed for monitoring, it is also useful to install inexpensive manual rain gages at the monitoring site to check the accuracy, consistency, and proper functioning among the different gages. Variation between gage measurements can occur because of gage location (i.e., elevation or microclimate) or they can be erroneous for other reasons (e.g., improper installation or placement or natural interferences such as birds resting on the gage or tree shadows). When significant variation is observed, it is important to identify the cause and correct it. Calibration about twice a year is important.

3.1.2 Collection of Other Meteorological Data

In addition to precipitation, other meteorological data such as temperature, humidity, wind speed, barometric pressure, and evapotranspiration may be desired to assess site conditions and BMP performance. These data are especially important for LID sites where water balance computations are needed to estimate watershed-wide effects (see Chapter 8). For infiltration oriented BMPs, temperature (and hence, frozen subsurface conditions) is important to document. This section briefly discusses some of the equipment that can be used to collect meteorological data in addition to rainfall.

3.1.2.1 Atmometers

The evapotranspiration of reference crops (ET_o) can be estimated using an atmometer. This device consists of a reservoir that supplies distilled water to a porous ceramic plate covered with a canvas material. The ceramic plate and canvas mimic the stomatal resistance of either alfalfa or turfgrass. The canvas, typically colored green, additionally mimics the albedo of vegetation covered land. As a wick draws water from the reservoir to the plate and canvas to be evaporated, the water level is measured with time to determine the rate of evaporation.

3.1.2.2 Weather Stations

Complete weather stations are commercially available as complete units that typically monitor the following meteorological parameters:

- precipitation
- temperature
- humidity
- wind speed and direction
- barometric pressure

As with rain gages, the placement of weather stations is critical for the collection of representative and accurate data. Ideally, weather stations should be located in the open and away from buildings, trees, or other objects that may affect measurements. The various sensors may need to be placed in different locations. For example, temperature and humidity, measured with thermometers and hygrometers, should be measured in the shade to avoid being biased by direct solar radiation, but away from vegetation. Conversely, 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.

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. As previously noted, temperature can affect infiltration and is important to document in many LID studies.

3.2 Flow Measurement Methods

Natural channels, engineered open channels, and pipes are used as stormwater conveyances. In each case, hydraulic considerations dictate the mathematical relationships that can be used to describe the flow rate at a given point in time. One of the primary hydraulic considerations is whether the flow configuration represents an “open” or “closed” channel. For example, open channel flow has a free water surface that varies with depth because the flow is driven by gravity. Closed channel flow, in which the flow fills a conduit, is caused by and increases with the hydraulic pressure gradient. Some stormwater conveyance system pipes may function as open channels during periods of low storm runoff and as closed channels when the runoff volume becomes sufficiently large or when water is backed up due to downstream flow conditions (e.g., tide, river flooding). Under such surcharged flow conditions, discharge velocities typically are greater than open channel flow due to the hydraulic gradient. Surcharged sewers have been known to pop manholes.

In general, the flow rate in an open channel depends on the depth of flow along with several other factors (Chow 1959) including:

- Geometric shape and changes in shape and slope along the length of the channel (affects potential for development of turbulence and/or varied flow and therefore the choice of methods and instruments used for measurement of flow).

- Hydraulic roughness of the conveyance surface, whether natural or manmade (affects the energy losses of the flow).

- Rate at which the depth of flow changes over time (steady versus unsteady flow).

- Spatial scale over which the flow rate changes (uniform versus varied flow).

The measurement of the flow rate in an open channel is more difficult to obtain than that of a full pipe, because the free surface will change with respect to time. Typically, stormwater flow through BMPs can fit the open channel flow configuration. However, some BMPs are drained by pipe systems, which may flow full at times. Therefore, methods used to measure flow in full pipes are also discussed below.

Exhibit 3-6 summarizes available flow measurement methods, the requirements for their use, typical BMP use, and required equipment. Each of these methods is discussed in more detail in the following sections.

Exhibit 3-6. Flow Measurement Methods

Method	Major Requirements For Use	Typical BMP Use	Required Equipment
Stage-Based Weir/Flume	▪ Open flow ▪ Constraint will not cause flooding	▪ Manual or automatic sampling	▪ Weir/flume and depth measurer
Velocity-Based	▪ Entrained air or sediments (Doppler-based velocity devices)	▪ Automatic sampling	▪ Depth measurer and velocity meter
Volume-Based Direct Measurement Methods	▪ Low flow rates	▪ Calibrating equipment ▪ Manual sampling	▪ Container and stopwatch
Tracer Dilution	▪ Adequate turbulence and mixing length	▪ Typically used for calibrating equipment	▪ Tracer and concentration meter
Pump-Discharge	▪ All runoff into one pond	▪ Not typically used for BMPs	▪ Pump
Stage-Based Variable Gate Meter	▪ 4-, 6-, or 8-inch pipes only	▪ Not typically used for BMPs	▪ ISCO variable gate meter
Stage-Based Empirical Equations	▪ Open flow ▪ Known channel/pipe slope ▪ Channel slope, geometry, roughness consistent upstream	▪ Manual or automatic sampling	▪ Depth measurer

The most common flow measurements methods for BMP studies include: (1) Stage-Discharge; (2) Area-Velocity; (3) Direct Flow Measurement; (4) Dilution; and (5) Pumped Discharge.

3.2.1 Primary Flow Measurement Devices

This section provides an overview of the process of selecting a primary flow measurement device. Because of the broad range of storm flows experienced at many BMP studies, it is important that measurement devices be able to accurately monitor a broad range of runoff events, including small, frequently-occurring storms that account for the majority of runoff and pollutant loads in urban areas, as well as larger storms. The USBR (2001) identifies key factors influencing the selection of a flow measurement device. These include:

- Accuracy requirements
- Cost

- Legal constraints
- Range of flow rates
- Head loss
- Adaptability to site conditions
- Adaptability to variable operating conditions
- Type of measurements and records needed
- Operating requirements
- Ability to pass sediment and debris
- Longevity of device for given environment
- Maintenance requirements
- Construction and installation requirements
- Device standardization and calibration
- Field verification, troubleshooting, and repair
- User acceptance of new methods
- Vandalism potential
- Impact on environment

Primary flow measurement devices fall into two general categories, flumes and weirs. These devices allow for accurate measurement of discharge rates by creating a channel geometry in which the hydraulics are controlled (a “control section”). Using a known empirical equation, primary devices are calibrated (i.e., in the laboratory or by the manufacturer) to relate the stage at a predetermined point in the control section to the discharge rate. (For examples, see Granato et al. 2003.) These types of measurement devices are called depth-based (or stage-based) methods because the discharge through the device is directly related to the depth (stage or head) of the flow. The relationship between the depth of flow and the discharge is called the “rating.” Tables referred to as rating curves are available for all standard flumes and weirs and are easily accessible from multiple sources such as the USBR Water Measurement Manual (http://www.usbr.gov/pmts/hydraulics_lab/pubs/wmm/).

Exhibit 3-7. U.S. Bureau of Reclamation Water Measurement Manual Water Measurement Device Selection Guidelines

(USBR, 2001. Table 4-2. http://www.usbr.gov/pmts/hydraulics_lab/pubs/wmm/)

[Symbol Notes: "+": advantageous aspects; "-" negative features; "0": neutral. These symbols are relative indicators comparing application of water measurement devices to the listed criteria."v" denotes device suitability varies widely, "na" denotes not applicable to criteria.]

Device	Accur-acy	Cost	Flows >150 ft^3/s	Flows <10 ft^3/s	Flow span	Head loss	Site conditions			
							Lined canal	Unlined canal	Short full pipe	Closed conduit
Sharp-crested weirs	0	0	-	+	0	-	-	0	na	na
Broad-crested weirs	0	+	+	+	+	0	+	0	na	na
Long-throated flumes	0	0	+	+	+	0	+	0	na	na
Short-throated flumes	0	-	-	0	0	-	-	0	na	na
Submerged orifices (in channels)	0	0	-	+	-	-	0	0	na	na
Current metering	-	-	+	-	-	+	0	-	na	na
Acoustic velocity meters in open channel	-	0	0	-	0	+	0	0	na	na
Radial and sluice gates	-	+	0	0	-	-	+	+	+	na
Propeller meters at pipe exit	-	+	-	0	0	+	0	0	+	+
Differential head meters for pipe[1]	+	-	-	+	-	V	na	na	0	+
Mechanical velocity meters for pipe[2]	0	+	-	0	0	+	na	na	0	+
Magnetic meters for pipe	0	0	-	0	0	+	na	na	-	+
Acoustic Doppler ultrasonic meters for pipe	-	0	-	-	-	+	na	na	-	+
Acoustic flowmeter pipe (single path)	0	-	0	0	0	+	na	na	-	+
Acoustic flowmeter pipe (multipath)	+	-	+	0	+	+	na	na	-	+

[1] Venturi, orifice, pitot tube, shunt meters, etc.

[2] Propeller meters, turbine meters, paddle wheel meters, etc.

Additional Consider-ations	Measure-ments		Sediment/ Debris Pass.		Longevity		Mainte-nance	Constr-uction	Field verifi-cation	Standard-ization
	Rate	Vol-ume	Sedi ment	Debris	Moving parts	Elec tricity needs				
Sharp-crested weirs	+	-	-	-	+	+	0	-	0	+
Broad-crested weirs	+	-	0	+	+	+	+	+	+	0
Long-throated flumes	+	-	0	+	+	+	+	0	+	0
Short-throated flumes	+	-	0	+	+	+	+	-	-	+
Sub-merged orifices (in channel)	+	-	-	-	+	+	+	0	+	0
Current metering	+	-	+	+	0	0	0	+	0	+
Acoustic velocity meters in open channel	+	0	+	+	0	-	-	+	-	-
Radial and sluice gates	+	-	0	-	+	0	+	+	-	-
Propeller meters at pipe exit	0	+	0	-	-	0	-	+	0	0
Differential head meters for pipe[1]	+	-	-	v	+	0	0	0	+	+
Mechanical velocity meters for pipe[2]	v	v	-	-	-	0	-	0	0	0
Magnetic meters (pipe)	+	0	0	0	0	-	-	0	-	0
Acoustic Doppler ultrasonic meters (pipe)	+	0	0	0	0	-	-	0	-	-
Acoustic flow meter pipe (single path)	0	+	0	0	0	-	-	-	-	0
Acoustic flow meter pipe (multipath)	+	+	0	0	0	-	-	-	-	+

[1] Venturi, orifice, pitot tube, shunt meters, etc.
[2] Propeller meters, turbine meters, paddle wheel meters, etc.

3.2.1.1 Weirs

A weir is a designed obstruction (usually a vertical plane) built or placed across an open channel or within a pipe under open channel flow so that water flows over the weir's top edge or through a well-defined opening in the plane. Many types of weirs can be used to measure discharge. The three most common weirs are: the rectangular; trapezoidal (or Cipolletti weir); and triangular weirs. The weir opening (i.e., the rectangular, trapezoidal, or triangular opening) is called the "notch." Each type of weir has a specific discharge equation for determining the flow rate through the weir.

Compared to flumes, weirs are generally low in cost, easy to install, and can be quite accurate when used correctly. A weir can be used to regulate flow in a natural channel with irregular geometry—a situation where Manning's Equation, for example, would not provide reliable estimates for the flow rate. Weirs are generally used for flow measurements with relatively large head available to establish free-flow conditions over the weir. While a weir can be used to regulate flow, it creates a partial dam causing backwater. During large storm events, the backwater may cause or exacerbate flooding upstream, particularly in a closed conduit. Some jurisdictions prohibit the use of weirs for this reason.

When evaluating the suitability of a monitoring site for a weir, it is important to determine whether the system was "over designed." That is, will the conveyance be able to move the design capacity after weir installation? In the case where the downstream depth of flow is greater than the crest of the weir (i.e., the weir is submerged), a different stage-flow relationship for the weir will apply.

Weirs are often not a good choice where representative suspended sediment samples are desired because larger sediment particles tend to settle above the weir, particularly during low flow conditions. Sediments and debris that accumulate behind a weir can also 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.

3.2.1.2 Flumes

A flume is a specially built channel (most often a prefabricated insert) with a converging entrance section, a throat section, and diverging exit section.

Because the velocity of water accelerates as it passes through a flume, the problem of sedimentation associated with weirs as described above is avoided; however, problems with debris accumulation in a flume can still occur. Flumes reduce the backwater effect by introducing a lower headloss than weirs. A flume may be more expensive and difficult to install than a weir because of its more complex design; however, where applicable, flumes can provide accurate results and significantly reduce maintenance issues.

The most common types of flumes are the Palmer-Bowlus, the HS, H, and HL flumes, and the trapezoidal flume. Parshall flumes have also been commonly used historically, but long-throated flumes are now recommended instead of Parshall flumes (USBR 2001).

Exhibit 3-8. Thel-Mar Weir (Parson Environmental)

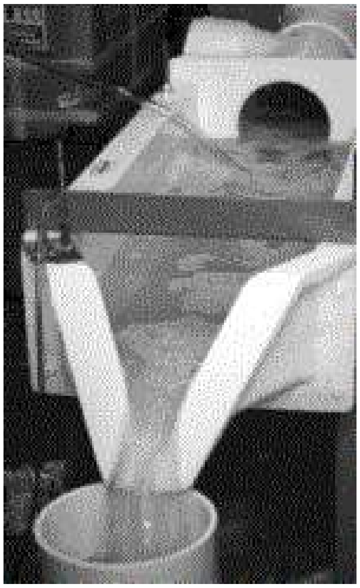

Exhibit 3-9. H-flume (Tracom Inc.)

3.2.1.3 Selection Considerations

There are many factors to consider when selecting a primary flow measurement device as summarized in Exhibit 3-10. These factors may include range of flows, accuracy, cost, head loss and flow characteristics, sediment and debris, and construction requirements, all of which are investigated below.

Range of Flows

Many measurement devices have a limited range of flow conditions for which they are applicable. This range is usually related to the need for certain prescribed flow conditions which are assumed in the development of calibrations. Large errors in measurement can occur when the flow is outside this range (USBR 2001). Several examples include:

- Thel-Mar weirs: These are composite weirs that provide measurement over a large range of flows from low to high. A V-notch is used for accurate low flow measurements and a broad-crested weir for high flow measurements. A challenge associated with this weir is that it uses less than 50 percent of the cross-sectional area of the pipe in which it is installed, limiting accurate measurement of pipe-full flows.

- Triangular thin-plate weirs: These weirs have a large range in their ability to measure flows because of the 2.5-power relationship between flow depth and flow rate. That is, relative to other devices, flow increases quite rapidly as a function of head. The range of flow rates that can be measured accurately can vary by a factor (ratio of largest flow to smallest flow rate) of 200 for fully contracted weirs to a factor of around 600 for partially contracted 90^{o} notches that utilize the allowable range of head (ASTM 1995).

- Rectangular thin-plate weirs: The range of measurement for these weirs typically varies from a factor of about 90 to about 110 for full-width weirs. These ranges depend somewhat on the crest length to channel width ratio. These results are based on a minimum head of 0.1 ft (0.03 m) and a suggested (although not absolute) maximum head of 2 ft (0.6 m). However, the range of measurement of smaller rectangular weirs can be significantly less (ASTM 1995).

- Parshall flumes: Although Parshall flumes are in extensive use in many western irrigation projects, they are no longer generally recommended because of the advantages of long-throated flumes and some significant disadvantages of Parshall flumes. Designing and setting Parshall flumes for submerged flow measurement is not usually recommended because less expensive, long-throated flumes can be designed that approach or exceed 90 percent submergence limits with a single upstream head measurement. Moreover, the absolute required drop in water surface is usually less for the long-throated flumes, particularly the modified broad-crested weir styles (USBR 2001). (See http://www.usbr.gov/pmts/hydraulics_lab/pubs/wmm/chap08_10.html for more information.)

- Palmer-Bowlus and other long-throated flumes: The range of measurement for these flumes depends on the shape of the throat cross-section. The range increases as the shape varies from rectangular toward triangular. For typical Palmer-Bowlus flumes of trapezoidal section, the range of flow rates that can be measured accurately generally varies by a factor of 30. The USGS has also developed and tested a modified Palmer-Bowlus flume (USGS 1985) for use in circular pipes that carry highway stormwater runoff. Flow can occur under either open or pressurized flow. These flumes measure the discharge under pressurized flow by using two bubbler sensors, which detect the hydraulic pressure change between upstream and downstream locations on the flume. This system was found to be one of the most accurate after calibration was performed. However the range between low and high flows that can be measured accurately using a Palmer-Bowlus flume is not as large as some other types of devices.

- H, HS or HL flumes: The use of H, HS, or HL flumes should be considered when measuring extreme flow ranges along with sediment transport capabilities, as is often the case for stormwater runoff. The range of flows that can be measured accurately using all varieties of H-type flumes can exceed three orders of magnitude; for example, a 3 ft H-flume can measure flows between 0.0347 cfs at 0.10 ft of head to 29.40 cfs at 2.95 ft of head.

- Nested Flumes: For some cases when low flows are expected to occur for an extended period but will ultimately be superseded by much larger flow rates, the interim use of removable small flumes inserted inside larger flumes can provide a method for accurate measurement of the range of flows.

In summary, small and moderate flows are generally best measured with thin-plate weirs, with the triangular notches most appropriate for the smallest flows (ASTM 1995). Small Palmer-Bowlus flumes are also useful in measuring low flows. While these flumes do not have issues related to sediment passage and head loss as do thin-plated weirs, they have the potential to be less accurate (ASTM 1995). Flumes and broad-crested weirs are generally the best choices for the measurement of large discharges.

Accuracy

When selecting a primary flow measurement device, it is important to consider the accuracy. Weirs are generally recognized as more accurate than flumes (Grant and Dawson 1997). A properly installed weir can typically achieve accuracies of 2 to 5 percent of the rate of flow, while flumes can typically achieve accuracies of 3 to 10 percent (Spitzer 1996). However, ASTM cites lower errors for weirs ranging from about 1 to 3 percent and Palmer-Bowlus flumes with typical accuracies around 5 percent.

The overall accuracy of the flow measurement system depends on a number of factors, including proper installation, proper location for head measurement, regular maintenance, the accuracy of the method employed to measure the flow depth, approach velocities (when using weirs), and turbulence in the flow channel (when using flumes). The largest source of error in flow measurement of stormwater typically results from inaccuracies related to low flow or unsteady flow; however, significant measurement errors are also caused by improper construction, installation, or lack of maintenance. A silted weir or inaccurately constructed flume can have associated errors of ±5 to 10 percent or more (Grant and Dawson 1997). Circumstances present in many stormwater monitoring locations can result in errors well in excess of 100 percent.

Potential inaccuracies in the method used to measure the depth of flow tend to increase the error in flow measurement as the flow depth approaches the minimum head. For primary devices operating near minimum head, even a modest error can have a significant effect on the measured flow rate. Therefore, it is important to select sizes or combinations of primary devices that avoid prolonged operation near minimum head (Spitzer 1997). It is also important to understand the limitations of the stated accuracy of flow measurement devices. A device that states an accuracy of 1 to 2 percent at optimal operating conditions may have a much poorer accuracy for flow conditions that are less than optimal (e.g., low flow/shallow depths).

One possible approach to reducing inherent error associated with each flow measurement device is to use the same type of device at each location associated with the study in an effort to balance errors. This may be a realistic option at some studies where comparable conditions exist for inflows and outflows, but at locations where inflow and outflow characteristics differ significantly, it is more important to select a device expected to have the highest accuracy for the expected flow conditions.

In situ calibration of meters and other equipment can also help to reduce errors.

Cost

It is important to consider the manufacturing, installation, and operational costs when selecting a primary flow measuring device. Weirs are often considerably less expensive to fabricate than flumes due to simpler design and material requirements (Grant and Dawson 1997). Weirs are also usually easier and less expensive to install, although installation of flumes designed for insertion into a pipe (e.g., Palmer-Bowlus and Leopold-Lagco) are generally straightforward. Despite the higher initial costs of flumes, the relatively low maintenance requirements may outweigh those costs with time (Grant and Dawson 1997). Consideration should be given to the expected sediment loads in the flow to be measured for likely accumulation and maintenance requirements for weir installations.

Head Loss and Flow Characteristics

The head difference that is required for a weir or flume to operate properly can also be an important selection criterion. Examples include cases where the elevation difference is not adequate to maintain the minimum required flow or where the upstream channel cannot contain the backwater. Under comparable flow conditions, thin plate weirs typically require the largest head difference, and the long-throated flumes require the least amount of head (ASTM 1995). Parshall flumes require an intermediate amount of head, but are no longer recommended for use.

Weirs are typically gravity fed and must be operated within the available head of the system. Flumes also require a certain head range in which the flow level is low enough so that it does not exert back pressure on the water in the throat of the flume. If a flume does not have sufficient head range, it will be in a submerged condition thus requiring two head measurements to accurately determine the flow rate.

Operation of a weir is sensitive to the approach velocity, often necessitating a stilling basin or pond upstream of the weir to reduce the fluid velocity. Operation of a flume is sensitive to turbulence or waves upstream from the entrance to the flume, which can require a section of straight channel upstream of the flume.

Sediment and Debris

Sediment and debris is another factor to consider when choosing a primary flow measurement device. Flumes tend to be self-cleaning because of the high flow velocity and the lack of any obstruction across the channel (Spitzer 1997). Therefore, a flume is generally more suited to flow channels carrying solids than is a weir.

Debris accumulation is likely to occur behind a weir, especially when a stilling basin is present to reduce flow velocities to an acceptable rate. Debris accumulation behind a weir can affect flow measurement and may even interfere with water quality measurements. This requires periodic inspection and maintenance to remove debris. To allow periodic removal of deposits, it is recommended that the weir bulkhead be constructed with an opening beneath the notch to sluice accumulated sediments (Spitzer 1997).

Flumes, while typically not susceptible to problems due to sedimentation, can have debris accumulate in the throat portion of the flume and require periodic maintenance. This maintenance is generally required less frequently than it is for weirs.

Construction Requirements

When selecting a primary flow measuring device, it is important to consider construction requirements as each differs in shape and complexity. The Parshall flume is usually the most difficult device to construct due to the relatively complex shape and the possible need to excavate the channel floor to accommodate the sharp downward slope of the throat. Because flumes are empirical devices, it is necessary to closely follow the design specifications (ASTM 1995). The discharge coefficients for long-throated flumes can be obtained theoretically which allows for some departure from the prescribed dimensions. Many types of flumes are available in prefabricated sizes up to several feet in width.

Weirs are generally easier to construct than flumes due to their more simplistic design. The most difficult task when constructing a weir is the fabrication of the notch edges, which require a sharp edge so the nappe is free flowing.

3.2.2 Secondary Flow Measurement Devices

A variety of instruments can be used to measure water depth. Because some techniques are relatively cumbersome, they are more useful for calibrating equipment than for routine or continuous data collection during storm events. The equipment required for each technique and the associated advantages and disadvantages for sampling runoff at BMP sites are described below. Exhibit 3-10 summarizes the equipment available for measuring depth of flow, important requirements for use of this equipment, and how this equipment is typically used within a BMP monitoring program. When selecting measurement devices, it is important to carefully consider practical factors such as site conditions and instrument and cable housing. For example, some types of cable housing do not function for long-term continuous monitoring and can be damaged if placed in the sampling stream for extended periods of time. Teflon® cable housing can be used to extend life span. Additional discussion on several methods follows. Regardless of the method used, the importance of proper calibration procedures and frequencies cannot be overstated.

Exhibit 3-10. Equipment for Measuring Depth of Flow

Method	Major Requirements For Use	Typical Use in a BMP Monitoring Program
Visual Observations	Small number of sites and events to be sampled. No significant health and safety concerns.	Manual sampling
Float Gage	Stilling well required.	Manual or automatic sampling
Bubbler Tube	Open channel flow. No velocities greater than 5 ft/sec.	Automatic sampling
Pressure Transducer	Less “drift” if remains submerged between events.	Automatic sampling
Ultrasonic Depth Sensor	Open channel flow. No significant wind, loud noises, turbulence, foam, steam, or floating oil and grease.	Automatic sampling
Ultrasonic Uplooking	No sediments or obstructions likely to cause errors in measurement.	Automatic sampling
Radar/Microwave	Similar to Ultrasonic Depth Sensor but can see through mist and foam.	Automatic sampling
3-D Point Measurement	Highly controlled systems. Typically not useful in the field.	Automatic sampling
Pressure Probe	Open channel flow. No organic solvents or inorganic acids and bases.	Automatic sampling

3.2.2.1 Float Gage

A float gage is used to measure changes in water surface elevation to determine flow rates. A float gage consists of a float that is free to move up and down in response to the rising and falling water surface in a channel. Prior to an actual stormwater sampling event, the site is calibrated to establish an initial reference depth. During the storm, the float rises and falls with changes in water surface elevation, and a device attached to the float records the magnitude of these changes. The changes in water surface elevation are converted to depth of flow by the float gage. A data logger can then record the depth of flow, and if capable of performing mathematical equations, determine the flow rate. If the data logger does not have the capability to do these types of calculations, data can be inputted into appropriate software to compute the flow rate.

In some applications, the use of a float gage requires a stilling well. A stilling well is a reservoir of water connected to the side of the conveyance that isolates the float and counterweight from turbulence in the main body of the flow. Retrofitting an existing channel or conduit with a stilling well can be a potentially expensive and time-consuming process and a principal drawback of this technique. However, this method can be useful if sampling is conducted at a site where a float gage and stilling well have been previously installed.

3.2.2.2 Bubbler Tube

Bubbler tubes are used by some types of automated flow meters to measure the depth of flow. Compressed air (or gas) is forced through a submerged tube attached to the channel invert (i.e., bottom of the channel). A pressure transducer measures the pressure needed to force a bubble out of the tube. This pressure, in turn, is linearly related to the depth of the overlying water:

$$P = \rho h \qquad \textbf{Equation 3-1}$$

Where:

P: hydrostatic pressure, N/m^2 (lb/ft^2)
ρ: specific weight of water, N/m^3 (lb/ft^3)
h: depth of water, m (ft)

Bubbler tubes are commonly integrated with a flow meter, or a data logger that is capable of performing mathematical calculations. This approach allows the measurement of depth to be immediately converted to a flow. These real-time inputs, along with a program that tracks accumulated flow volumes, can be used to trigger the collection of samples for flow-weighted compositing by an automated sampler.

Exhibit 3-11. Bubbler Flow Meter (ISCO)

Bubbler tubes are simple to use and are not usually affected by wind, turbulence, foam, steam, or air-temperature gradients. Accuracy is not lost under dry conditions in a conveyance between runoff events (some other types of probes must remain submerged). Although they are generally reliable, bubblers are susceptible to error under high velocity flow. That is, as flow velocity increases to over 1.5 to 1.8 m/s (5-6 ft/sec), a low pressure zone is induced around the mouth of the bubbler tube, interpreted by the flow meter as a drop in flow rate. These instruments, therefore, should not be used in channels where the slope of the bottom exceeds 5 to 7 percent. Sediments and organic material can also plug bubbler tubes. Some units are periodically purged with compressed air or gas to prevent this problem, but visual inspection and periodic maintenance are recommended for any unit installed in the field. Bubblers can be problematic for winter monitoring if the bubbler is pressurized through a diaphragm, which can become brittle and break at below freezing temperatures. Bubblers are commonly available in integrated systems, such as those manufactured by ISCO and American Sigma, but are also sold as independent devices.

3.2.2.3 Ultrasonic Depth Sensor

An ultrasonic depth sensor consists of a sonar-like device mounted above the surface of the water at a known distance above the bottom of the channel. A transducer emits a sound wave and measures the period of time taken for the wave to travel to the surface of the water and back to a receiver. This time period is converted to a distance and then converted to a depth of flow, based on measurements of the site configuration. As with bubbler tubes, an ultrasonic sensor can be integrated into a flow meter or interfaced with a data logger. An ultrasonic depth sensor and data logger can provide the real-time flow data necessary to trigger an automated sampler to collect a stormwater sample for flow-weighted compositing.

Exhibit 3-12. Ultrasonic-Depth Sensor Module (ISCO)

Some manufacturers have built redundancy into their ultrasonic depth-measuring instruments. Redundancy helps to ensure that useful data can be collected even if some of the sensors in the array become fouled with grease, surface-active materials, or organisms. Experience has shown that this type of fouling can occur during storm events. Because an ultrasonic sensor is mounted above the predicted surface of the water, it is not exposed to contaminants in the runoff unless the depth is greater than anticipated or it is installed in a pipe that reaches fully pressurized flow. While this device is not generally affected by contaminants, ultrasonic signals can be adversely affected by wind conditions, loud noises, turbulence, foam, and steam. Ultrasonic signals can also be affected by changes in density associated with air temperature gradients; however, some manufacturers do build a compensation routine into their instruments. Because of these potential problems, periodic inspection and maintenance of these instruments is recommended.

Background noise can interfere with a sensor's ability to accurately measure water depth. For example, an ultrasonic sensor was used in Portland, Oregon to measure the depth of flow at an urban stormwater sampling site located in a manhole in which runoff from an arterial pipe splashed down into the main conveyance. To dampen the effect of the interfering signal, the ultrasonic sensor was retrofitted with a flexible noise guard.

3.2.2.4 Pressure Probe

A pressure probe consists of a transducer, mounted at the bottom of the channel that measures the hydrostatic pressure of the overlying water. This hydrostatic pressure is converted to a depth of flow. When selecting probes, it is important to select devices that are rated for hydrostatic pressures expected at the monitoring location. Additionally, some pressure probes have a built-in thermometer to measure the temperature of the water thus allowing for temperature compensation in the depth of flow calculation, which is important for accurate measurements. As with bubblers and ultrasonic probes, the pressure probe can be integrated into a flow meter or interfaced with a data logger to provide real-time inputs into an automated sampler. If the instrument is fitted with a thermometer, it is also possible for temperature data to be collected and stored for future use.

Exhibit 3-13. Pressure Transducers (In-Situ Inc.)

Submerged probes are not adversely affected by wind, turbulence, foam, steam, or air temperature gradients. However, because contaminants in the water may interfere with or damage the probe, periodic inspection and maintenance is recommended. Dry conditions between storms can affect the accuracy of the probe, as can sudden changes in temperature. Installation of a simple staff gage can also be useful in calibrating pressure probes.

3.2.2.5 Ultrasonic “Uplooking”

This depth-of-flow sensor is mounted at or near the bottom of the channel or pipe. It uses ultrasonic signals to determine the depth of the flow. Some vendors report that this equipment is not recommended for stormwater BMP influent because the sensor is likely to become covered by sediments and debris. This then interferes with the signal and does not allow the sensor to work properly. These sensors have, however, been successfully used to monitor BMP effluent.

3.2.2.6 Radar/Microwave

A variation of the ultrasonic method is a non-water contacting instrument that emits and reprocesses electromagnetic waves in the radar/microwave spectrum. By altering the wavelength of the electromagnetic signal, problems associated with foam, mist, and rapid changes in air temperature and pressure are eliminated or significantly reduced. A radar/microwave sensor is used in the same manner as an ultrasonic “downlooking” sensor for measuring fluid levels in tanks. Based on experience, this device does not present a significant advantage over other methods of level measurement, since foam and mist are not typically a large concern during stormwater monitoring. Radar/microwave sensors have not been extensively tested by manufacturers for this type of application, and there is no existing literature that shows them being used for stormwater monitoring.

3.2.3 Velocity-Based Methods

The continuity method is a velocity-based technique for estimating flow rate. Each determination requires the simultaneous measurement of velocity and depth of flow. Flow rate is calculated as the sum of the products of the velocity and the cross-sectional area of the flow at various points across the width of the channel:

$$Q = A_i * V_i$$ **Equation 3-2**

Where:

Q: flow, m^3/s (ft^3/sec)
A_i: cross-sectional area of the flow at planar section *i*, m^2 (ft^2)
V_i: mean velocity of the flow at section *i*, m/s (ft/sec)

In stormwater runoff applications, the conveyance is small enough that a single cross-sectional area and estimate of average velocity can typically be used to estimate flow rate. That is, it is not necessary to segment the cross-sectional area of the flow. The accuracy of this method depends on the ability of a sensor to measure velocity over a range of flow.

Although this method is useful for calibrating equipment, it is more sophisticated and expensive than the stage-flow relationships previously discussed. In addition, this method is suitable only for conditions of steady flow. That is, the water level must remain essentially constant over the period required for obtaining velocity measurements. This is not generally a problem in small conveyance systems when instruments that make measurements rapidly are employed.

Additionally, the Darcy-Weisbach equation can be used in systems where pressurized flow (i.e., pipes flowing full; no free water surface) is present and can be found in Gupta (1989).

Use of the continuity equation for measuring flow requires the estimation of average velocity as well as depth. The velocity of flow can be measured using visual methods (i.e., the float-and-stopwatch or the deflection/drag-body methods), tracer studies, the use of instruments such as rotating-element current meters and pressure, acoustic, ultrasonic (Doppler), and electromagnetic sensors. Electromagnetic sensors have been found to be the most accurate. Among these methods, many are more useful for the calibration of automated equipment than for continuous data collection. Only the ultrasonic and electromagnetic methods are recommended for measuring velocity during a storm.

When using any type of velocity meter over a range of flows, it is important to be aware of their limitations. For example, area-velocity (A-V) meters that will be used for low flow measurement will require installation of a structure to create a backwater condition. A-V meters require both a minimum depth for the depth measurement (~0.5 inch) and several inches for velocity measurement. A backwater condition is needed to ensure that both the depth and velocity instruments have minimum depth requirements.

3.2.3.1 Ultrasonic (Doppler) Sensors

An ultrasonic sensor applies the Doppler principle to estimate mean velocity. A sound wave, emitted into the water, reflects off particles and air bubbles in the flow. The shift in frequency of waves returning to the sensor is a measure of the velocity of the particles and bubbles in the flow stream. The instrument computes an average from the reflected frequencies, which is then converted to an estimate of the average velocity of the flow stream.

Exhibit 3-14. Area Velocity Sensors Module (ISCO)

The sensor is mounted at the bottom of the channel. However, because the ultrasonic signal bounces off suspended particles, the signal may be dampened and not able to reach portions of the flow stream when suspended particle concentrations are high. The sensor can also be mounted on the side of the channel, slightly above the invert to help reduce the impacts of bed load and solids accumulation on the sensor. Combined with the appropriate hardware and software, the sensor can filter out background signals associated with turbulence in the flow. Conversely, in ultra-clean water, the signal may "drop out" when there are not enough particles to reflect the signal.

Ultrasonic Doppler sensors can be used under conditions of either open channel or pressurized flow. When properly calibrated and combined with the hardware and software required for real-time flow measurement, data logging, and automated sampling, this system is capable of greater accuracy than systems that rely on a stage-flow (i.e., Manning's Equation) relationship. The ultrasonic sensor-based system can be more expensive but the additional expense may be justified by program objectives. Routine maintenance of ultrasonic sensors is recommended to prevent inaccuracies from fouling by surface-active materials and organisms.

3.2.3.2 Electromagnetic Sensors

Electromagnetic sensors work under the principle stated in Faraday's Law of electromagnetic induction: a conductor (i.e., water) moving through an electromagnetic field generates a voltage proportional to its velocity. The sensor is mounted at or near the channel bottom where it generates an electromagnetic field and measures the voltage inducted by the flow. Although velocity is measured at only a single point, that measurement is used to estimate the average velocity of the flow stream.

Electromagnetic sensors can be pre-calibrated for many types of site configurations. While the sensor is usually mounted at the channel invert, it can be mounted on the side of a channel, slightly above the invert, if high solids loadings are expected. A built-in conductivity probe senses when there is no flow in the conveyance.

Electromagnetic instruments are not sensitive to air bubbles in the water or changing particle concentrations like the ultrasonic sensors, but they can be affected by extraneous electrical "noise." As with the ultrasonic system, when an electromagnetic sensor is properly calibrated and combined with the hardware and software required for real-time flow measurement, data logging, and automated sampling, it is capable of greater accuracy in specific circumstances than a system relying on a stage-discharge relationship. The electromagnetic sensor-based system can be more expensive, but the additional expense may be justified by program objectives.

3.2.3.3 Acoustic Path

These sensors are used to determine the mean velocity of streams and rivers, and where they are applicable, they have been found to be one of the most accurate flow measurement systems. The method consists of an array of sensor elements that are installed at an even elevation across the channel. The number of sensor elements used is dictated by the channel width (i.e., larger channels require more sensors). Due to the sensor array's height above the channel bottom, its use is generally limited to larger channels that have a base flow present. These sensors have been successfully used in backwater and tidal conditions where the multi-layer sensors were able to measure layers of water moving in different directions in large outfalls (Personal Communication with Robert Pitt, University of Alabama, 2009). It is not a practical method to use for smaller diameter conveyances with no base flow, which may be found at a BMP site. Additionally, stormwater conduits for BMP runoff can be small enough that a single point measurement for velocity provides a reasonable estimate for the average velocity. For these reasons, acoustic path sensors are rarely applicable to BMP monitoring situations.

3.2.3.4 Rotating-Element Current Meters

A current meter or current meter array can be used to measure the velocity at various points throughout a flow stream. The measured point velocities can be combined to estimate a mean velocity for the flow. As with the deflection or drag-body method, if employed for longer periods, a current meter inserted into the flow can accumulate debris causing it to malfunction and possibly break away. Therefore, this method should only be used for short-term measurements such as during equipment calibration or to develop a rating curve. Two types of readily available instruments that meet USGS standards are the type AA Price and Pigmy current meters.

3.2.3.5 Pressure Sensors

A pressure sensor or transducer measures the dynamic pressure head at a given point in the flow. The dynamic pressure is a measure of the point velocity and can be used to estimate the mean velocity of the flow. A common example of a pressure sensor is the Pitot tube used on an airplane or on some boat speedometers.

The same caution described for bubbler tubes must be applied to pressure sensors as well. That is, as the velocity of the flow increases above 1.5 to 1.8 m/s (5-6 ft/sec), a low pressure zone is induced across the sensor and interpreted by the flow meter as a drop in flow rate. These instruments should not be used in channels where the slope of the bottom exceeds 5 to 7 percent.

3.2.3.6 Acoustical Sensors

An acoustical sensor emits a sound wave under water across a channel and measures the time required for the signal's return. Transit time is correlated with channel width. The relative positions of the emitting and receiving sensors are used to estimate velocity. A minimum depth of flow is required to use this sensor effectively. Also, this type of sensor can only be used at sites with sufficient base flow to provide the medium in which the sound wave travels. If there is no base flow, the lower portions of the rising and falling limbs of the hydrograph are lost.

3.2.3.7 Float-and-Stopwatch Method

In this method, the time it takes for a float to move a known distance downstream is determined. Velocity is calculated as the distance traversed divided by the travel time. The characteristics of a good float are: an object that floats such that it is partially submerged, allowing some averaging of velocity above and below the surface of the water; an object that is easily observed and tracked; an object that is not easily affected by wind; and an object that does not cause problems if not recovered. Citrus fruits such as oranges, limes, or lemons are commonly used as floats. Ping-pong and styrofoam balls float well but are too light and are easily blown by the wind; they can also pose environmental problems if not recovered.

One variation of this method is the use of a vertical float with a weighted end. The vertical float provides a better measure of mean velocity over the depth of the water column than a float moving primarily at the surface. In addition, this type of float can be designed to minimize bias due to wind.

In most cases, the float-and-stopwatch method is not accurate enough to be of significant use in stormwater monitoring studies. It is also particularly inaccurate for very deep systems and where there is a significant difference in velocity across the water surface (e.g., natural channels).

3.2.3.8 Head Stick Estimated Flow

For approximate flow measurement using minimum equipment, the "head stick" method can be used by following these steps:

1) Place a ruler in the flowline of the channel so that the edge of the ruler is paralleled to the flow line. The ruler should be more or less streamlined. Record the depth measured on the ruler (d_1).

2) Rotate the ruler 90 degrees so that the flat surface of the ruler is perpendicular to flow. Record the depth (d_2). The difference between d_2 and d_1 is the velocity head.

3) Calculate the velocity (V) as follows:

$$\Delta h = d_2 - d_1 = \frac{V^2}{2g}$$

$$V^2 = (d_2 - d_1) \cdot 2g$$

$$V = \sqrt{(d_2 - d_1) \cdot 2g} \qquad \textbf{Equation 3-3}$$

Where:

V: velocity (ft)
G: gravitational acceleration (32.2 ft/s^2)
d_2, d_1: recorded depths (ft). (Note: If depth in inches, convert to feet.)

4) Flow can be calculated using the velocity estimate and cross sectional area of flow.

3.2.3.9 Deflection (or Drag-Body) Method

In this method, the deflection or drag induced by the current on a vane or sphere is used to measure the flow velocity. This method is only practical for short-term, real-time measurements, such as equipment calibration, because an object of this size inserted into the flow can accumulate debris, causing it to change the hydraulic form, provide inconsistent data, and potentially break away.

3.2.3.10 Tracer Studies

Tracer methods have been developed to measure flow velocity under uniform flow (USGS 1980). For Total Recovery Tracer studies, as described in the flow measurement methods section, a discrete slug of tracer is injected into the flow. Concentration-time curves are then constructed at two downstream locations. By determining the time for the peak concentration of the dye plume to pass the known distance between these two locations, one can estimate the mean velocity of the flow. This method is not practical for continuous flow measurement, but is useful for site calibration. As previously noted, this method is not appropriate for areas affected by combined sewer overflows (CSOs).

3.2.3.11 Methods Suitable for Calibration

The most important aspect of any calibration method is its ability to obtain accurate results with a high degree of certainty and repeatability. Proper calibration of equipment is essential in reducing flow measurement errors. A variety of methods have been employed in the past. The most common methods are described in this section. Exhibit 3-15 summarizes the available methods.

Exhibit 3-15. Velocity Measurement Methods Suitable for Calibration

Method	**Comments**
Tracer Studies	Although one of the best calibration methods, it is often not practical. Requires complete mixing of tracer with flows.
Rotating-Element Current Meters	Useful for larger flows that do not rapidly vary with time. Typically useful for large systems with appreciable flows. Low flows are difficult to monitor.
Pressure Sensors	Not useful for velocities above 1.5-1.8 m/sec or in pipes with steep slopes (>5%).
Acoustical Sensors	Not applicable to most monitoring locations. Large flow rates are typically required. Base flow required to observe complete storm hydrograph. Typically applicable only to large channels.
Float and Stopwatch	Rarely accurate enough for calibration purposes. Not recommended for most situations
Bucket and Stopwatch	Although not a velocity method, this approach can work very well for determining flow rates and may be a very useful tool for flow rate calibration.
Deflection (or Drag-Body) Method	Rarely accurate enough for calibration purposes. Not recommended for most situations.

3.2.4 Data Loggers

Where automated data collection is desired over time, secondary devices typically are attached to data loggers. Data loggers are devices that monitor signals from instruments and store the impulses that they generate. When data loggers are combined with software to measure and route signals between instruments and analyze data, they are referred to as "data acquisition systems" and are often used as the execution center of a monitoring station. Most data loggers have multiple input ports and can accommodate a variety of sensory devices, such as temperature probes, rainfall gages, or pressure transducers.

Some vendors provide automated water quality sampling and/or weather station "monitoring systems" that have intrinsic data loggers that will accommodate inputs from the typical sensors that would be associated with the type of monitoring that the system is designed to accomplish and a central processing unit (CPU) with limited programming and data processing capabilities. Often, these "monitoring systems" are adequate for standard BMP monitoring applications and can greatly simplify monitoring station setup.

One drawback of these "monitoring systems" is that often times they can only support sensors from the same vendor that provided the system. 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

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. They are designed to operate at extreme temperatures, from as low as -55°C to as high as 85°C (-67°F to 185°F). 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.

Exhibit 3-16. Data Logger with Weatherproof Housing (Handar)

A typical data logger for field use may consist 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 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 (e.g., PC, PDA) connected to the communications port on the logger. Data stored Memory may be retrieved by downloading to personal computers (PCs) or personal digital assistants (PDAs), data transfer units (DTU), or via remote access (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.

Exhibit 3-17. Data Logger Without Housing (Campbell Scientific)

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 are available. For long-term, unattended monitoring projects, a fixed instrument capable of serving as a remote transmitting unit may be preferable to a portable one. Manufacturers of data loggers suitable for stormwater monitoring can be easiliy obtained through simple internet searches.

3.2.4.1 Programmability

Some data loggers can be programmed to convert the signals they receive directly into useful information such as velocity, flow, or rainfall depth. These data loggers can be programmed to interrogate a sensor at user-selected data recording time intervals. Once the intervals are set, the data logger can collect the information and record the output (e.g., the voltage or resistance output from a pressure transducer sensor), or it can record an “exception” if the sensor output goes outside a defined range (e.g., break in signal when a rainfall gage bucket tips). The data logger can then develop simple statistics based on the input they receive.

Less expensive models can be pre-programmed at the factory to collect data at a defined interval or to count exceptions. In this case, the user must post-process the downloaded information to create meaningful data.

Many vendors offer data loggers with the capability of remote manipulation via modem and PC, however, the user-friendliness of the various models can vary greatly between vendors. These data loggers require vendor-developed software packages and an IBM-compatible PC with Windows™ to run the packages. Therefore, this additional cost should be considered when evaluating a particular model. Another point of consideration is the format in which a particular model logs the data it receives. Some models log data in a format that can be converted from ASCII files to any of several commonly available spreadsheet or word processing files, while others require the use of their particular vendor-developed software for data analysis and manipulation.

3.2.4.2 Data Capacity

Memory type and capacity vary greatly between instruments. Standard capacity varies between models and vendors from less than 8 Kilobytes to several gigabytes with removable flash memory. In general, one data point uses 2 bytes of information; therefore, a data logger with 64K of memory can be expected to have a maximum data point capacity of 32,000 data points before downloading data or requiring more memory to be added. Some types of sensor inputs require as much as 4 bytes of memory per data point; these would require data loggers with more memory capacity. It should also be noted that when recording sets of data related to storm events, memory can be exhausted more quickly than expected.

Most data loggers use a non-volatile Flash type of memory for data storage. That means that no power is required to store data once it is recorded. However, some data loggers store programs and data on volatile RAM-type memory. All information stored on volatile RAM is lost if the power is cut off. For these data loggers, an automatically activated backup power source is recommended. Backup power is usually a lithium battery that requires frequent monitoring and replacement every 1 to 10 years.

Most models are programmed to stop recording data upon exhaustion of available memory. However, some models are equipped with wraparound or rotary memory, which rewrites over the oldest data when available memory becomes exhausted. When using rotary memory, it is important to realize that data can be lost if it is not downloaded before it is written over.

Systems with data loggers that are separate from water quality samplers are more flexible than combined data/samplers because they are more programmable. Memory capacity is often an issue (even with the current inexpensive memory) and requires that careful attention be paid to downloading data before it is overwritten.

3.2.4.3 Communications

Models vary in their ability to accept input from more than one source. Significant advances have been made in recent years in this regard. Some data loggers are designed with a single analog input channel, while others are designed with up to 16 channels. In addition, some of the newer models accept digital input data. The choice of a particular model should be based upon the number of sensors or probes from which the instrument will be required to accept data.

Data loggers can accept information from many different types of sensors and transducers. This allows for versatile use of most data logging systems. Some vendors offer probes and transducers with built-in data loggers; however, these systems typically cannot accept input data from other sensory devices, and their ability to communicate output data is often limited.

With regard to output communications, most data loggers interface with the standard RS-232 interface type, and some possess the capability to communicate with other interface types. In most cases, data can be downloaded on-site to a laptop PC or transported to a lab or office so that the data can be downloaded to a desktop PC. As indicated earlier, data loggers can be equipped with an internal modem for telecommunications, allowing a user to download data from a remote host PC without having to visit the field site.

In most cases, use of a telephone modem requires an IBM-compatible PC as the host as well as the vendor's software. Typically, baud rates can be selected by the user. However, some models are capable of only a few baud rates, a limitation that should be considered when choosing a specific model. Some machines also possess the capability to transmit data via line-of-sight, UHF/VHF or satellite radio. These options also allow for remote manipulation of programming and downloading of data.

With rapidly occurring changes in communication technology, this is a constantly improving component of stormwater monitoring. Advances in recent years include cellular modems, sattelite technologies and other emerging communication technologies.

3.2.4.4 Power Requirements

In general, data loggers are energy efficient devices. Most are powered by an internal battery, with the option of using external electrical power, if available. Because power is lost during some storms, batteries should be the primary power source, although they can be recharged from other sources. Many devices are also equipped to use solar power. Data loggers can also be powered by internal batteries. In this case, there is often a choice of cell type. While some models offer the choice of rechargeable cells or standard 12-volt alkaline cells, others offer alkaline lithium batteries. The power source and model selected generally depends upon several factors, including site accessibility, distance from the nearest point on the electric power grid, and amount of data to be recorded.

When evaluating power options, the battery replacement and disposal costs should be considered along with the estimated life of the battery. For example, alkaline cells are less expensive than lithium or rechargeable batteries, but they have a shorter life and must be replaced more often. While alkaline cells offer a potential power life of several months, lithium cells offer a potential power life of several years. However, since lithium batteries are considered a hazardous material, data loggers using lithium batteries are subject to more stringent shipping requirements than models using standard alkaline cells. In addition, since alkaline batteries must be replaced and discarded frequently, the use of alkaline batteries may actually be more expensive than using rechargeable batteries. Although rechargeable batteries offer less battery waste and potential cost savings, the time and cost required to recharge the batteries should be considered when evaluating power options.

Operating temperature range is another important factor to consider when choosing a power supply. Lithium expands both the minimum and maximum temperatures at which power can be used by the data logger. Under extreme conditions, it may not be feasible to use a data logger powered by alkaline batteries.

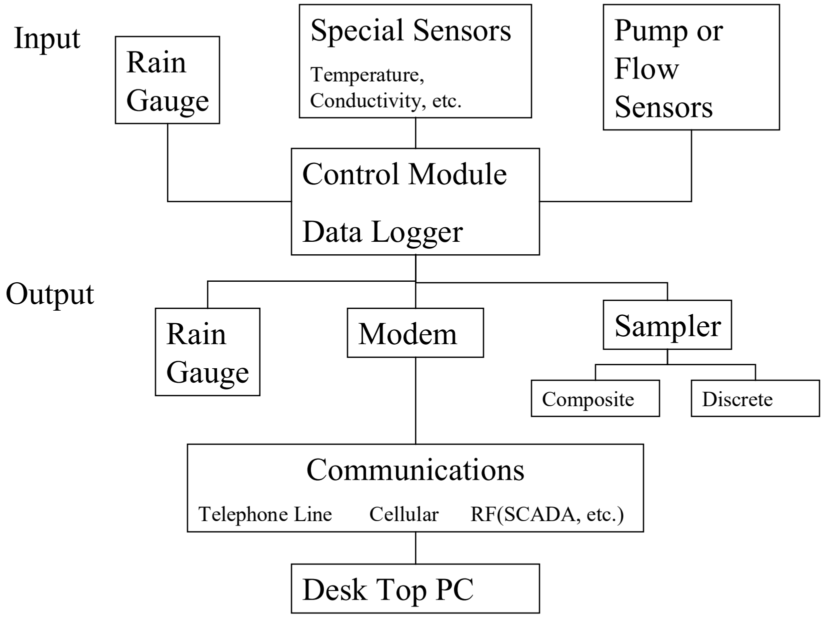

Exhibit 3-18. Data Logger Summary

3.2.5 Other Flow Measurement Methods

In addition to the primarily automated flow monitoring methods previously described, other methods also exist that may be appropriate and useful in various situations. These include direct measurement methods, tracer dilution methods, pump discharge methods, and stage-based equations, as described in the following sections.

3.2.5.1 Direct Measurement Methods

Flow rate can be directly measured by estimating the time it takes to fill a receptacle of known volume or the time it takes to drain a storage basin with a known volume based on the relationship described in Equation 3-4:

$$Q = V/T \qquad \textbf{Equation 3-4}$$

Where:

Q: flow in m^3/s (ft^3/s)
V: volume, m^3 (ft^3)
T: time in seconds.

This method is easy to understand, requires relatively simple equipment, and can be very accurate at low rates of flow. Simply use a bucket with known capacity at predetermined level to capture water and a stopwatch to measure the time it takes to capture that volume. Typically, multiple measurements are made and the results are averaged.

This method requires the complete capture of the flow stream during the measurement interval and is most often used for conducting limited research and for calibrating equipment. However, this method can also be used to obtain estimates of average discharge rates from a treatment facility, provided that the flow is fairly uniform.

3.2.5.2 Tracer Dilution Methods

Tracer dilution methods can be used where the flow stream turbulence and the mixing length are sufficient to ensure that an injected tracer is completely mixed throughout the flow stream (USGS 1980; Gupta 1989). Tracers are chosen so that they can be distinguished from other substances in the flow. For example, chloride ion can be injected into fresh water, and dyes or fluorescent material can be used if turbidity is not too high. Dye calibration does not work well where CSOs are present.

Dilution studies are well suited for short-term measurements of turbulent flow in natural channels and in many manmade structures such as pipes and canals. However, these methods are better suited to equipment calibration than to continuous monitoring during a storm event. Two dilution methods can be used to determine flow rate, including:

- Constant Injection Rate Tracer Dilution Studies: In this study, a known concentration of tracer is injected at a constant rate into a channel. The concentration of the tracer in the flow is measured at a downstream point over time. Flow is calculated from the initial tracer concentration, the tracer injection rate, and the steady-state downstream concentration. The changes in concentration of the dye reflect changes in flow, which makes this method especially useful during an actual runoff event with highly varying flows. Use a downstream sampler to collect discrete samples that are taken to a lab for fluorescence determinations and compare with calibration curve made from injection dye stock and upgradient water. Create several sets of calibration curves for different times to compensate for potential changes in interferences.

- Total Recovery Tracer Dilution Studies: In this study, a discrete slug of tracer is injected into the channel. Near-continuous measurements of tracer concentration in the flow are taken at a downstream point until the plume has entirely passed. Flow is calculated from the volume and concentration of injected tracer and the total area under the concentration-time curve.

3.2.5.3 Pump Discharge Method

In some cases, the overall discharge rate for a catchment can be measured as the volume of water that is pumped out of a basin per unit time while holding the water level in the basin constant. This method can be applied at sites where flow runs into a natural or manmade basin from several directions or as overland flow. If the pump is already calibrated, then the number of revolutions per minute, or the electrical energy needed to pump a given volume, can be used as a surrogate to measure the pumped volume during a stormwater runoff event.

A considerable amount of knowledge about the installed pump's performance is required to implement this method. While the pump discharge method is one option available to measure the runoff volumes, it is not typically used in the field because other methods are often easier to implement and are more accurate; therefore, pumps are not discussed further in this manual.

3.2.5.4 Stage-Based Variable Gate Meters

ISCO produces a Variable Gate Metering Insert. In this device, discharge flows through the insert and under a pivoting gate, which creates an elevated upstream level that is measured with a bubbler system. The meter uses an empirical relationship to calculate the discharge rate based on the angle of the gate and the depth of flow upstream of the gate. This approach can be used only under conditions of open channel flow in circular pipes. Currently the system is only available for pipe diameters of 10.16, 15.24, and 20.32 cm (4, 6, and 8 inches).

The Variable Gate Metering Insert is designed to measure the flow rate under fluctuating flows and can be effective at both very high and very low flow rates. Its main limitation is the size of the conveyance for which it is designed. The insert may be useful for sampling very small catchment areas; however, debris accumulation can occur, causing problems with the meter.

3.2.5.5 Stage-Based Equations

In cases where measurement of flows is not possible, mathematical equations such as Manning's and Chezy's Equations may be used to estimate flows. If used, it is critically important that those using the equations understand their proper use and associated limitations.

Manning's Equation

The most commonly used empirical relationship, the Manning Equation, is appropriate for open channels with steady-state and uniform flow conditions. In other words, it is used in locations where the flow rate does not vary rapidly over time and the depth of flow does not vary over the length of the channel (Gupta 1989). The Manning Equation (Equations 3-5 and 3-6) requires data for these variables: the slope of the energy grade line, which is usually assumed to be the slope of the channel bottom; the cross-sectional area of the flow; the wetted perimeter; and an empirical roughness coefficient, which accounts for channel material, age, and physical condition.

$$Q = \frac{1}{n} AR^{2/3}S^{1/2}$$

Equation 3-5

$$Q = \frac{1.486}{n} AR^{2/3}S^{1/2}$$

Equation 3-6

Where:	Where:
Q: flow, m^3/s	Q: flow, ft^3/s
n: Manning roughness coefficient (dimensionless)	n: Manning roughness coefficient (dimensionless)
A: cross sectional area, m^2	A: cross sectional area, ft^2
R: hydraulic radius, m (area per wetted perimeter)	R: hydraulic radius, m (area per wetted perimeter)
S: slope of the channel, m/m	S: slope of the channel, ft/ft

While the Manning Equation only truly applies to steady and uniform flow, it can provide a fairly accurate estimate of flow rates if certain conditions are met. For example, the channel slope and cross-sectional geometry must be constant for some distance upstream of the site, the exact distance varying with overall system hydraulics. As a rule of thumb, the distance used is the length of twenty channel diameters, or forty hydraulic radii upstream. In addition, flow conditions at the site should not be affected by downstream features (i.e., no backwater effects). Additional information on applicability and values for Manning's roughness coefficients for common channel types are provided in most hydraulics texts (Chow 1959; Gupta 1989). Researchers should be aware, however, that these roughness coefficients are intended for design purposes and, at times, are larger than roughness values based on back-calculation from field-measured flows. Additionally, they can very greatly with depth of flow, debris, and other factors.

Use of the Manning Equation assumes that the slope of the channel bottom is accurately known. Monitoring studies using this technique to estimate flow rates often rely on as-built drawings to determine channel slope. Because these drawings vary in accuracy, direct measurement of the slope of the channel bottom and verification of hydraulic conditions is recommended.

The flow rate of stormwater runoff tends to be unsteady. This is due to changes in the intensity of precipitation and the dynamic nature of overland flow, which can cause the flow rate to vary gradually or rapidly with time. Depending on the frequency with which the depth of flow is measured, rapid fluctuations in flow rate can be missed and the total runoff volume from a storm event can be miscalculated. It is important to calibrate use of the equation with site conditions based on continuous stage measurements and dye injection, or another calibration method.

Chézy Equation

Another empirical relationship used to estimate flow is the Chézy Equation (Gupta, 1989):

$$\frac{Q}{A} = C\sqrt{RS}$$

Equation 3-7

Where:

Q: flow, m^3/s (ft^3/s)
A: cross-sectional area, m^2 (ft^2)
R: hydraulic radius, m (ft)
S: slope of the energy grade line, m/m (ft/ft)
C: flow coefficient, $m^{1/2}/s$ ($ft^{1/2}/s$)

Under open channel flow, the coefficient "C" can be defined as:

$$C = \frac{R^{1/6}}{n}$$ **Equation 3-8**

Where:

n: Manning's Roughness Coefficient

When "C" is substituted into Chézy's Equation, the resulting equation is identical to the Manning Equation.

A limitation of both the Manning and Chézy Equations is that they imply that the Manning "n" value is constant for a given channel. However, it is known that for natural channels "n" may vary greatly with respect to flow (Ponce 1989). Therefore, when considering applying these equations to a natural channel, one should first evaluate the alluvial material in the channel and the magnitude of flows expected. It may be desirable to select another flow measurement approach for natural channels with highly varied surfaces and flow rates.

3.2.6 QA/QC of Flow Measurements

Quality assurance and quality control programs (QA/QC) need to be established at the beginning of a project to ensure that precipitation and stormwater flow measurements are accurate and representative of the flow system investigated. Granato et al. (2003) recommend that an effective QA/QC program for stormwater flow data collection activities should include:

- Frequent and routine site visits by trained/experienced field personnel.
- Redundant methods for measuring precipitation and stormwater flow.
- Technical training for project personnel.
- Frequent review by project personnel of precipitation and stormwater-flow data collected.
- Quality audits, in the form of periodic internal reviews.
- Quality audits, in the form of periodic external reviews.

For specific procedures to determine probe accuracy, precision and drift, and to QA/QC-associated discharge measurements, see the references listed in Exhibit 3-1 of this chapter, as well as manufacturer user's guides associated with monitoring equipment.

3.2.7 Infiltration Estimates

Methods to estimate and measure infiltration are discussed in more detail in Chapter 8 in the context of LID; however, estimates of infiltration are valuable for all BMPs, providing a check on the accuracy of hydrology measurements and providing a basis of comparison of hydrologic benefits from LID to conventional BMPs.

3.2.8 Common Flow Monitoring Challenges for LID Techniques

Because most LID techniques are intentionally designed to disperse flows (avoid concentration) and infiltrate runoff, flow monitoring can be challenging, but is likely the most important aspect of performance monitoring for LID. Chapter 8 discusses LID monitoring strategies in more detail; nonetheless, the discussion below provides some practical tips on monitoring common LID practices.

- <u>Pervious Pavements</u>: When monitoring pervious pavements, careful experimental design is needed for both influent and effluent. Influent monitoring presents the unique challenge of not having any runoff to monitor unless there is run-on to the pavement surface from adjacent impervious areas. Influent flow monitoring can be done by either monitoring precipitation at the site and converting it to flow, or by monitoring flow from a nearby location and then scaling the flow proportionally to the areas. For influent water quality monitoring, an adjacent area should be selected with land use and proximity as close as possible. Ideally, this would be an area immediately adjacent with comparable traffic usage. Effluent monitoring is typically done through subdrains, as is the case for many LID techniques. Effluent subdrain monitoring should consider the amount of storage, if any, provided in a subbase reservoir below the subdrain. Groundwater monitoring wells can provide important monitoring data with respect to migration of subsurface contaminants, groundwater mounding, and seasonal high water levels. Catch basins and common surface grading are commonly present at pervious pavement sites as a redundancy measure and can be used for monitoring bypassed flows. Bypass monitoring is more important for failing pavements, but may not be needed for functional sites (Personal Communication with Rob Roseen, University of New Hampshire, 2009).

- <u>Calculating (Modeling) Flows as an Alternative to Flow Measurement</u>: Because LID designs inherently seek to disperse flow, rather than concentrate it, inflow measurement for BMPs can be challenging. However, if other parameters are accurately measured, it may be possible to calculate or model inflow. For example, at a bioinfiltration site monitored by the Villanova Urban Stormwater Partnership (VUSP), inflows cannot be monitored, but water depth in the infiltration "bowl", rainfall and overflow can be measured. VUSP has developed and calibrated a hydrologic model to calculate inflows.

3.3 Conclusions

A wide range of hydrologic and hydraulic monitoring approaches are available for urban stormwater BMP monitoring. Selection of equipment is based on site-specific conditions, budget, and desired accuracy. Defensible hydrologic monitoring is fundamental to BMP performance analysis, particularly as many communities are placing increased emphasis on techniques that promote volume reduction.

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Chapter 4
WATER QUALITY MONITORING

This chapter provides guidance for collection of water quality samples for assessment of stormwater Best Management Practice (BMP) performance. It is intended to be used in conjunction with Chapter 2 Developing a Monitoring Plan and Chapter 3 Hydrologic and Hydraulic Monitoring. Topics addressed include: water quality parameters and analytical methods; selection of sampling locations; considerations for collecting discrete and composite samples, manual sampling, and automatic sampling; and field and laboratory QA/QC. Water quality monitoring is a multifaceted, complex topic that is the subject of many textbooks and manuals. For more information on specific topics, Exhibit 4-1 lists several references that provide more detail.

Exhibit 4-1. Resources for More Detailed Information on Water Quality Monitoring

Burton and Pitt. 2001. *Stormwater Effects Handbook: A Toolbox for Watershed Managers, Scientists, and Engineers*. http://www.epa.gov/ednnrmrl/publications/books/handbook/index.htm

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4.1 Water Quality Parameters and Analytical Methods

4.1.1 Selecting Parameters

Stormwater runoff may contain a variety of substances that can adversely affect the beneficial uses of receiving water bodies. To select the parameters to be analyzed for a given monitoring location, consider the following:

- Permit requirements (if any). Permit requirements often specify both the analyte and required analytical method.
- Land uses in the catchment area and associated pollutants. Sources such as the BMP Database (http://www.bmpdatabase.org) and the National Stormwater Quality Database (http://rpitt.eng.ua.edu/Research/ms4/Paper/Mainms4paper.html) have considerable information on pollutants associated with various land uses.
- Existing monitoring data (if any) for the catchment area. Previous monitoring data can be helpful in refining the parameter list; however, it is important to understand the purposes and methods of previous studies to place the data in context.
- Beneficial uses of the receiving water. Information on water quality within a stormwater drainage system often is used to indicate whether discharges from the system are likely to adversely affect the receiving water body.
- Anticipated pollutant removal mechanisms and targeted pollutants for BMP being monitored. When selecting analytes, it may be beneficial to include parameters associated with the targeted pollutant, as well as inexpensive parameters with similar characteristics to the target pollutant that can serve as surrogates. For example, if total phosphorus is the regulated parameter, it may also be beneficial to include orthophosphate since BMP effectiveness may be influenced by the portion of total phosphorus that is in the dissolved form. Additionally, inexpensive basic water quality characterization parameters such as temperature, conductivity, and pH among others should typically be included.
- Overall program objectives and resources. The parameter list should be adjusted to match resources (personnel, funds, time).

If program objectives require assessing a large number of parameters (based on a review of land uses, prior monitoring data, and so on), consider a screening approach where samples collected during the first one or two storms are analyzed for a broad range of parameters of potential concern. Parameters that are not detected, or are measured at levels well below concern, can then be dropped from some or all subsequent monitoring events. To increase the probability of detecting the full range of pollutants, the initial screening samples should be collected from storms that occur after prolonged dry periods.

A recommended list of basic constituents (along with recommended method detection limits enabling comparison of stormwater samples to water quality criteria) for BMP monitoring is presented in Exhibit 4-2 below. The choice of which constituents to include as standard parameters is somewhat subjective and, ultimately, site-specific conditions and study objectives must be considered. It is important to note that not all of the parameters listed in Exhibit 4-2 are suitable for automatic samplers—some level of manual sampling would also be required to evaluate all of the listed parameters.

The following factors were considered in developing the recommended list of monitoring parameters:

- The pollutant has been identified as prevalent in typical urban stormwater at concentrations that could cause water quality impairment (EPA 1983; Pitt et al. 2004; and recent municipal National Pollutant Discharge Elimination System data).
- The analytical result can be related back to potential water quality impairment.
- Sampling methods for the pollutant are straightforward and reliable for a moderately careful investigator.
- Analysis of the pollutant is economical on a widespread basis.
- Some parameters are listed because they may affect the function of some BMPs or affect the toxicity of certain pollutants, even if the parameter itself is not a pollutant of concern. For example, temperature can affect the function of infiltration facilities; pH and temperature can affect ammonia toxicity to aquatic life; and hardness and pH can affect toxicity of certain metals.

A few practical comments regarding analyte groups include:

- Nutrients: Where budget constraints are an issue, total phosphorus and total nitrogen should be the minimum parameters to monitor, thereby avoiding additional filtration, preservation, and processing requirements associated with other forms of the analytes. Nutrients can repartition or be metabolized during storms. As with metals, the speciation of nutrients during stormflows may be less important than the post-discharge concentrations in receiving waters. For some types of BMPs, it may be more meaningful to characterize geochemical redistribution of nutrients within BMPs between storms than to focus on within-storm transport. For more information on nutrient monitoring, see Hem (1992) and EPA (2000). For regulatory background, see EPA's Water Quality Criteria for Nitrogen and Phosphorus Pollution website (http://www.epa.gov/waterscience/criteria/nutrient/).
- Organic Compounds: Organic compounds include polycyclic aromatic hydrocarbons (PAHs), other semi-volatiles, volatiles, herbicides, and pesticides. Sampling of these compounds is not addressed in detail in this manual. Nonetheless, there are a number of issues to be considered. For example, containers (metal and glass) and processing materials recommended for sampling organics are not recommended for sampling metals. Automatic samplers can increase volatilization by suction and by squirting samples into vented containers. Many organic compounds are commonly measured at or near detection

limits. Therefore, protocols are more sensitive to contamination and data are harder to analyze. As with metals, many organic compounds are associated with sediments. Whole-water sampling may be a better strategy for sampling organic compounds. See Shelton (1997) and Shelton and Capel (1994) for more information.

- Metals: There are a number of issues associated with metals sampling, which are discussed in Section 4.1.2.

- Suspended Solids and Gross Solids: Since the original release of this monitoring manual in 2002, substantial research has been conducted related to issues associated with monitoring suspended solids and gross solids. These topics are discussed in Sections 4.1.3 and 4.1.4. (Sampling of deposited sediments is discussed in Section 4.4.)

- Microbiology: At the time this manual was released, EPA was in the process of revising recreational water quality criteria, including considering whether alternative microbiological indicators of fecal contamination should be used. See EPA's Recreation Water Quality Criteria website (http://www.epa.gov/waterscience/criteria/recreation/) for the latest information on this effort. In the interim, Section 4.1.5 provides a brief discussion of some microbiological monitoring issues.

As a final note, researchers should also keep in mind that probe-measured parameters such as specific conductance, turbidity, and others can be used to augment information from limited water quality sampling efforts requiring laboratory analysis. For example, flow and specific conductance can be used to estimate annual inlet and outlet loads of chlorides. Specific conductance records can also provide a "free" tracer test. Continuous monitoring records from probes can also provide helpful context for data from sampled storms. For more information, see *Guidelines and Standard Procedures for Continuous Water-Quality Monitors: Station Operation, Record Computation, and Data Reporting* (Wagner et al. 2003, http://pubs.usgs.gov/tm/).

Exhibit 4-2.
Typical Urban Stormwater Runoff Constituents and Recommended Detection Limits

Parameter	Common Units	Target Detection Limit
Conventional		
pH	s.u.	N/A
Conductivity	µs/cm	N/A
Temperature	C	N/A
Turbidity	n.t.u.	5.0
Total Suspended Solids (TSS)	mg/L	5.0
Suspended Sediment Concentration (SSC)	mg/L	5.0
Total Hardness	mg/L	1.0
Chloride	mg/L	1.0
Bacteria[1]		
Fecal Coliform	MPN/100 mL	2
E. coli	MPN/100 mL	2
Enterococci	MPN/100 mL	2
Nutrients[2]		
Orthophosphate	mg/L	0.05
Total Phosphorus	mg/L	0.05
Total Kjeldahl Nitrogen	mg/L	0.1
Nitrate + Nitrite	mg/L	0.05
Ammonia Nitrogen	mg/L	0.1
Metals—Total Recoverable		
Cadmium	µg/L	0.2
Copper	µg/L	1
Lead	µg/L	0.2
Zinc	µg/L	1
Metals Dissolved		
Cadmium	µg/L	0.2
Copper	µg/L	1
Lead	µg/L	0.2
Zinc	µg/L	1
Organics		
Organophosphate Pesticides (scan)	µg/L	0.05 - 0.2
Hydrocarbons		
Total Petroleum Hydrocarbons	mg/L	0.5

Note: This list includes constituents found in typical urban stormwater runoff. Additional parameters may be needed to address site specific concerns. See Strecker (1994) and Urbonas and Stahre (1993) for additional guidance.

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[1] The upper quantitation limit is typically more significant for bacteria in stormwater monitoring data, which are prone to be right-censored, as opposed to left-censored.

[2] Nutrient contamination of receiving waters such as lakes and the Gulf of Mexico is resulting in greater attention to the various forms of nutrients in runoff. For this reason, multiple forms of nitrogen have been included in this list.

4.1.2 Dissolved vs. Total Metals

Different metal forms (species) show different levels of toxic effects. In general, metals are most toxic in their dissolved, or free ionic form. Specifically, EPA developed revised criteria for the following dissolved metals: cadmium, chromium, copper, lead, nickel, silver, selenium, and zinc. Arsenic and iron are assessed based on total recoverable forms. Total mercury criteria were developed based on mercury residuals in aquatic organisms (food chain effects) rather than based on toxicity. For comparisons with dissolved metal water quality criteria, the dissolved metals fraction usually needs to be determined in some manner. This can either be determined by sample analysis, or in some cases through models.

Analysis results for "dissolved metals" should be reported in the context of type and nominal pore size of filter used in the laboratory analysis. This supplemental information helps the user to differentiate whether the metals are truly ionic or potentially colloidal and complexed. There are many important issues with "dissolved" metals, which are more appropriately characterized as "filtered" metals (Clark 2009). In actuality, only a small proportion of the metals in a filtered water sample may be in the dissolved state as the majority are adsorbed to colloids or bound to humic or fulvic compounds. Other problems include sample contamination, adsorption, desorption, digestion issues, pre- and post-processing holding times, under-acidification, over-acidification, sample splitting procedural problems, and so on. Dissolved metals can partition and repartition within the time required to collect and process a stormflow sample. Dissolved metal sampling artifacts can also significantly affect measured concentration. Because many trace elements are associated with solids, there are more detection-limit issues with filtered metals (Granato et al. 2002).

Other factors to consider with regard to the distribution of pollutants between the dissolved and particulate phases includes where in the system the sample is collected. Runoff collected in pipes with little sediment will generally have a higher percentage of pollutants present in the dissolved form. Runoff collected in receiving waters will generally have a higher percentage of pollutants present in particulate form due to higher concentrations of suspended solids that act as adsorption sites for pollutants. It is difficult to determine how much of the dissolved pollutants found in storm system pipes will remain in the dissolved form when they are mixed with suspended sediments in receiving waters. As a result, it is difficult to determine the ecological significance of moderate levels of dissolved pollutants present within the conveyance system. In addition, hardness and pH values for receiving waters are often different than those for stormwater. For example, in some areas, hardness of runoff appears to increase as it travels across concrete surfaces; therefore, the chemical composition of the drainage system may also have an impact on total versus dissolved metals concentrations (Clark 2009). Hardness and pH affect the bio-availability of heavy metals, further complicating prediction of the ecological impact of dissolved heavy metals. If loads to the receiving waters are of concern (e.g., discharge to a lake known to be a water quality limited water body), it may be desirable to determine total recoverable metals to assess the relative load from different sources. Total recoverable metals data can also be used to assess potential issues involving metals in sediment.

An alternative to dissolved metals analysis is modeling of geochemical speciation of the metals in the runoff, in the BMP, and in the receiving water. If sediment, pH, alkalinity, major ions, hardness, and dissolved organic compounds (DOC) are sampled, models can be used to estimate metals partitioning. For example, EPA has adopted a biotic ligand model for copper, and WERF is working on biotic ligand models for nickel and other metals. The cost and effort required for collecting pH, major ions, and DOC for a biotic ligand model are much less than the cost for ultra clean (high purity) sampling (e.g., Teflon® equipment, high purity filters, high purity acid, extra samplers for clean-hands-dirty-hands sampling) (Granato 2009).

On a related note, researchers conducting work in multiple locations should be aware that dissolved metals data are less transferable than whole-water metals data because of the previously discussed data quality issues, the varying geochemical conditions that will occur at a given site from storm-to-storm and season-to-season, and the varying geochemical conditions that will occur from site-to-site and region-to-region. For these reasons, researchers should strongly consider collection of whole-water metals and related geochemical data, as an alternative to dissolved metals monitoring. The geochemical data may ultimately be more transferable because this information can be used with geochemical or biotic ligand models to examine conditions that may mobilize metals. With regard to BMP selection, geochemical redistribution of metals within BMPs between storms may be more important to characterize than within-storm transport (Granato 2009).

Finally, if monitoring objectives and site-specific conditions necessitate dissolved metals analysis, researchers should consider ultra-clean sampling procedures. Although ultra-clean monitoring protocols are not necessary for whole-water metal sampling, they have been shown to be very important for filtered-water sampling, even in contaminated waters. Much more operator and sample-processing equipment contact with the sample is needed to obtain a filtered water sample. Even if sampling artifacts are similar for filtered and whole-water samples, the artifacts will have a greater effect on the lower concentrations typically measured for filtered metals. Although ultra-clean monitoring protocols may not be practical in all monitoring studies, researchers should be aware of the issues associated with filtered metals results and carefully weigh the costs and benefits of ultra-clean sampling techniques (Granato 2009).

For more information on issues associated with dissolved versus total metals sampling, see the references in Exhibit 4-3.

Exhibit 4-3. Supplemental Information on Dissolved and Total Metals Monitoring

EPA. 1994. *The Biotic Ligand Model: Technical Support Document for Its Application to the Evaluation of Water Quality Criteria for Copper*. (EPA 822R03027). http://yosemite.epa.gov/water/owrccatalog.nsf/0/e693bcf79893c3e085256e23005fcd3b?OpenDocument

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Horowitz et al. 1994. *U.S. Geological Survey protocol for the collection and processing of surface-water samples for the subsequent determination of inorganic constituents in filtered water*. OFR 94-539. http://pubs.er.usgs.gov/usgspubs/citfor/ofr/ofr94539?currow=6

Water Environment Research Foundation (WERF). 2004. *Development of a Biotic Ligand Model for Nickel: Phase I.* http://www.werf.org/AM/CustomSource/Downloads/uGetExecutiveSummary.cfm?FILE=ES-01-ECO-10T.pdf&ContentFileID=7450

4.1.3 Measurement of Suspended Solids Concentration

A variety of methods have been employed in stormwater quality studies for quantifying sediment concentration in the water column. The most frequently cited parameter is "TSS" or total suspended solids; however, this label is often generically used to refer to more than one sample collection and sample analysis method, including:

- EPA Method 160.2: Total Suspended Solids (TSS) (Gravimetric, Dried at 103-105ºC). (USEPA 1999).

- American Society for Testing and Materials (ASTM) Method D3977-97(B): Standard Methods for Determining Sediment Concentration in Water (ASTM 1997). The USGS employs this suspended sediment concentration (SSC) method. SSC data are often described as TSS data, although results from the two methods may be significantly different in many cases.

- Standard Method (SM) 2540D: This TSS analytical method originated in wastewater analysis and is promulgated by the American Public Health Association in *Standard Methods for the Examination of Water and Wastewater* (APWA et al. 2005).

Differences in nominal filter pore size, sample mixing, aliquot size and method of aliquot collection, as summarized in Exhibit 4-4, can result in significantly different results from these methods (Clark and Siu 2008). Guo (2007) conducted tests to determine the relationships between the various test methods and found that SSC (using ASTM D3977-97(B)) results were very close to the true concentration of solids in laboratory tests, whereas the EPA Method 160.2 TSS measure was well correlated with SSC, but TSS using SM 2540D was not well correlated with SSC. The study also found that the difference between the SSC and EPA TSS results were well correlated with particle size, with increasing differences as particle size increased. Clark and Siu (2007) also concluded that correlations between the results and the known sample concentration could be established for TSS samples, dependent on the sample's particle size distribution and on the aliquot collection technique. These results emphasize the need to report not only the analytical method but also the particle size information on the solids in stormwater runoff.

Exhibit 4-4. Comparison of Three TSS/SSC Analytical Methods (Clark and Siu 2008)

Method Requirements	**USEPA TSS (160.2) and ISO (11923)**	**SM TSS (2540D)**	**ASTM SSC (D3977-97 (B))**
Filter Nominal Pore Size	not specified	<2.0 µm	1.5 µm (recommended)
Sample Mixing	shake vigorously	stir plate	decant supernatant and flush bottle with DI water
Aliquot Size	not specified	not specified	entire sample
Method of Aliquot Collection	pour aliquot into graduated cylinder	pipette at mid-depth in bottle; midway between wall and vortex	vortex pour from original bottle

One of the key differences between methods is sample size—the SSC method analyzes the entire sample, whereas the TSS method uses a sub-sample. The process of collecting a representative sub-sample containing larger sediment particles is problematic because large sediment particles (e.g., sand) often settle quickly. Differences between the results obtained from SSC and TSS analytical methods become apparent when sand-sized particles exceed 25 percent of the sample sediment mass (Gray et al. 2000). Gray demonstrates that at similar flow rates, sediment discharge values from SSC data can be more than an order of magnitude larger than those from TSS data (USGS 2001), due primarily to larger particles that are often missed in the TSS method. For this reason, the USGS's stated policy on the collection and use of TSS data is that TSS concentrations and resulting load calculations of suspended material in water samples collected from open channel flow are not appropriate (USGS 2001).

Another critical factor affecting comparability of data is the filter's nominal pore size. Analytical laboratories use filters with varying pores sizes obtained from various manufacturers. More complete documentation on the method type, filter size, and sample processing procedures is needed in many cases. In some cases, labs may use hybrid approaches from these methods, which necessitates better documentation for each component of the analysis.

To resolve potential interpretation issues regarding suspended sediment, it is recommended that both TSS (for comparison to existing data sets) and SSC be measured, when budgets allow. One of the reasons that this issue has received much attention is that various state and local regulations and technology verification protocols have chosen to use TSS as a performance measure, so a clear understanding of the TSS method and procedure used is important to performance evaluations.

Regardless of the analytical methods used, the sampling methodology often introduces the largest bias to sediment data. Properly installed autosamplers appear to be capable of collecting suspended sediment up to about 250 μm, but may have only about a 50 percent recovery for larger particles up to about 2 mm. If other sample fractions are desired, then bedload and floatable samples should compliment autosampler collection (Clark et al. 2009).

The discrepancies in sampling and analysis methodologies currently employed in the field highlight the importance of particle size distribution (PSD) analysis as an essential component of any BMP monitoring study to serve as a common denominator for comparing different analytical methods for sediment in runoff (Clark and Siu 2008). PSD data provide the information necessary to meaningfully interpret the ability of a BMP to remove suspended materials. PSD methods are varied and include (USGS 2001):

- Dry sieve
- Wet sieve
- Visual accumulation tube (VA)
- Bottom withdrawal tube
- Pipette (typical method)
- Microscopy
- Coulter counter
- Sedigraph (x-ray sedimentation)
- Brinkman particle size analyzer
- Laser diffraction spectroscopy
- Light-based image analysis

Another source of variability in suspended solids sample results is the lack of a standard protocol for sample preparation for particle size fractionation and analysis. For this reason, Pitt and Clark (2009) developed a sample preparation protocol to assist research laboratories in documenting a standardized protocol for sample preparation and testing so that performance results can be more appropriately compared. This protocol addresses gaps in guidance to produce a repeatable sample preparation technique, including these steps:

1) Set up a cone splitter for the desired number of subsamples, up to a maximum of 10, considering the needed analytical volumes for each subsample.

2) Place a 1200-μm cleaned mesh screen on top of the cone splitter and pour the entire sample through the mesh. The material retained on the mesh should be dried, weighed and saved for further analyses.

3) Split the remaining samples according to the required analyses with approximately half of the samples screened through a 250-μm sieve in order to characterize the fraction in the larger range (below the mesh size) that cannot be quantified as easily by a Coulter Counter Multisizer 3.

4) For samples requiring both TSS and SSC, set aside the appropriate subsamples. For verification protocol testing, this requires four aliquots: TSS unsieved; TSS sieved to less than 250 μm; SSC unsieved; and SSC sieved to less than 250 μm.

5) Filter TSS/SSC samples through the appropriate filter – either glass-fiber (if metals analyses are not required) or membrane (if metals analyses are required).

Specific gravity (SG) of sediments is also an important component in determining the settleability of sediments and is recommended for sediment analysis by ASTM (1997). For BMP studies where PSD data are being collected, SG provides additional useful information about the ability of a particular BMP to remove sediment. Settling velocities of sediments are highly important and can be either measured directly or calculated theoretically from SG and PSD data. Settling velocities give the most useful information for quantifying BMP sediment removal efficiency; however, historically, this information has not been frequently reported in typical stormwater BMP monitoring studies.

4.1.4 Measurements of Gross Solids

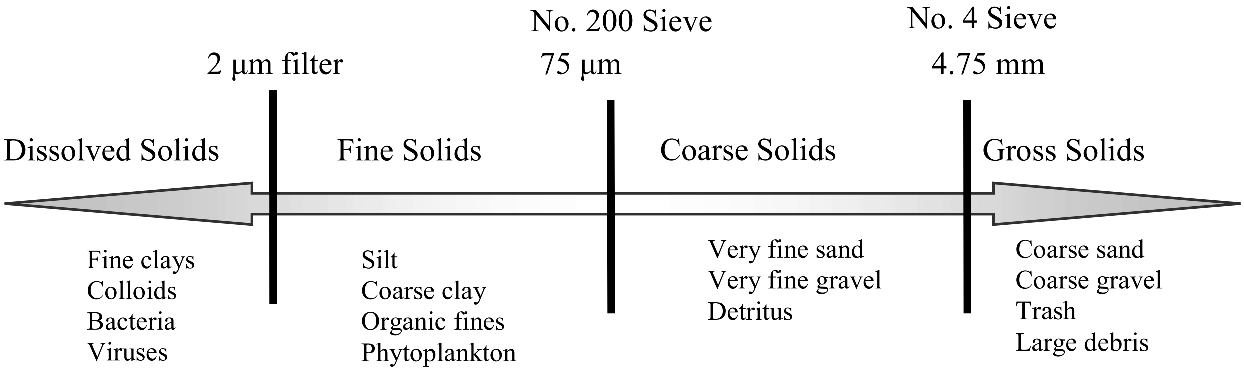
Closely related to measurement of TSS and SSC is the measurement of gross solids. Gross solids are the litter, trash, leaves, and coarse sediment that travel either as floating debris or as bedload in urban runoff conveyance systems. A variety of BMPs are designed to remove gross solids, including sediment basins, baffle boxes, hydrodynamic separators, oil/grit separators, modular treatment systems, and inlet traps, among others (EPA 2009). In 2009, the “ASCE Guideline for Monitoring Stormwater Gross Solids” was released by the Environmental and Water Resources Institute’s Urban Water Resources Research Council Gross Solids Technical Committee (Rushton et al. 2009), defining three gross solids categories as summarized in Exhibit 4-5. The gross solids guideline was developed for many reasons, one of which is that EPA has identified sediment as a cause of widespread impairment of the Nation’s rivers and streams. Additionally, an accurate quantification and characterization of all particle sizes, including gross pollutants, is needed for testing and evaluating BMPs in order to facilitate proper BMP design, as well as maintenance requirements and schedules. Furthermore, most gross solids cannot be sampled by traditional automatic samplers and have been ignored in studies evaluating the impact of storm water runoff on receiving waters (Rushton et al. 2009). The purpose of the ASCE guideline is to standardize data collection procedures used in evaluating the removal of gross solids by BMPs and also to allow for direct comparison of field data from separate studies by using the same collection methodologies.

Exhibit 4-5. Gross Solids Categories (*Source: ASCE Guideline for Monitoring Stormwater Gross Solids*, Rushton et al. 2009)

Category	Description
Litter	Human derived trash, such as paper, plastic, Styrofoam, metal and glass greater than 4.75 mm in size (#4 sieve)
Organic Debris	Leaves, branches, seeds, twigs and grass clippings greater than 4.75 mm in size (#4 sieve)
Coarse Sediments	Inorganic breakdown products from soils, pavement, or building materials greater than 75 microns. It also includes fragments of litter and organic debris not included in the other two categories. (#200 sieve).

Exhibit 4-5 builds upon solids classification work completed by Roesner et al. (2007), as summarized in Exhibit 4-6.

Exhibit 4-6. Solids Size Classification Diagram
(Source: Roesner et al. 2007)



The ASCE monitoring guideline for gross solids addresses a variety of factors, which vary according to the objectives of the monitoring program. The guideline should be referenced for more detail. An overview of the general topics included in the guideline based on monitoring program objectives is provided in Exhibit 4-7. The guideline also provides recommendations on sample collection techniques, contamination prevention, and sample compositing. Approaches to sampling include compositing sampling techniques developed by EPA (2006) and procedures for complete analysis of all samples by Roesner et al. (2007) and Sansalone and Kim (2008).

Exhibit 4-7.
Overview of ASCE Guideline for Gross Solids Monitoring —Program Level Summary

(Source: Rushton et al. 2009)

Level 1 **Minimal Monitoring** **(Screening Evaluation)**	**Level 2** **Detailed Monitoring** **(Performance Evaluation)**	**Level 3** **Advanced Monitoring** **(Research and Design)**
1. Rainfall amount 2. Time interval since last cleaning 3. Volume and weight of material captured in each chamber 4. Separation of large litter from coarse sediment and organic debris 5. At least two samples for chemical analysis of sediment/debris mixture 6. Percent organic matter of sediment/debris sample 7. Percent solids	1. Rainfall characteristics 2. Separation of organic debris from coarse sediment 3. Mass and weight of debris 4. Mass and weight of sediment 5. Sediment particle size distribution using sieve analysis 6. Chemical analysis for two debris samples per chamber 7. Chemical analysis for two sediment samples per chamber 8. Percent organic matter of sediment sample in each chamber 9. Water quality sampling using standard methods 10. Flow measurement for storm duration including bypass & baseflow	1. Sediment chemical analysis for each sieve size and whole sample 2. Additional chemical analysis for special parameters 3. Subdivide litter and debris into special categories 4. Baseflow measurement and chemical analysis 5. Leachate analysis 6. Mass balance 7. Other analysis as needed

4.1.5 Microbiological Sampling

Microbiological sampling has become increasingly important to stormwater managers because many streams throughout the country do not attain recreational water quality criteria established by EPA. As of publication of this monitoring manual, EPA was in the process of revising its Ambient Recreational Water Quality Criteria (EPA 1986); therefore, recommended microbiological sampling may change in the future. In the interim, communities undergoing the Total Maximum Daily Load (TMDL) process for non-attainment of recreational criteria will often monitor one or more indicator bacteria such as *E. coli, Enterococci*, or fecal coliform. While historically fecal coliform was typically monitored, *E. coli* or *Enterococci* are recommended as pathogen indicators for recreational criteria under current EPA criteria. *E. coli* is a bacterium found exclusively in the feces of humans and other warm-blooded animals and is used as an indication of fecal pollution and the possible presence of enteric pathogens. A limitation of *E. coli* as an indicator is that it can be present due to natural sources at levels that exceed stream standards and does not necessarily represent controllable sources of contamination of human origin.

A variety of microbiological methods are available following ASTM, IDEXX, Standard Methods and EPA methods. A discussion of each method is beyond the scope of this manual, however, the National Environmental Methods Index website (http://www.nemi.gov), can be referenced for more detailed information on over 30 current methods, including key information such as:

- General method information
- Media
- Method source (e.g., Standard Methods, ASTM)
- Brief method summary
- Scope and application
- Applicable concentration ranges
- Method download (links to websites)
- Interferences from other constituents
- QC requirements
- Sample handling
- Maximum holding time
- Relative cost/effort
- Sample preparation method(s)
- Precision descriptors
- Detection level notes

Representative challenges associated with microbiological sampling of stormwater include:

- Sample should be analyzed within six hours after sampling and within two hours from receipt of sample in lab for compliance monitoring or within 24 hours for routine monitoring (Standard Methods, 20th ed., Section 9060B); however, a six hour holding time for all samples is highly recommended (Myers and Sylvester 1997).

- Sample preservation requirements include chilling to 1 to 4 degrees C.

- For membrane filtration methods, sources of interference include: high turbidity, toxic compounds, or large numbers of non-coliform (background) bacteria, and organisms damaged by chlorine or toxic compounds. For example, samples with high levels of colloidal or suspended materials can clog the membrane filter pores and prevent filtration.

4.1.6 Analytical Methods

After the parameters have been selected, the analytical methods to be used to measure them must be chosen. Select analytical methods that will provide results of sufficient quality to support the intended uses of the data. To determine the quality of data necessary for a program, consider the following:

- Appropriate analytical levels: EPA guidance suggests tailoring the analytical level to the intended use of the data. EPA has defined five analytical levels:

  1) Field screening and analysis using portable instruments.

2) Field analysis using more sophisticated portable analytical instruments, possibly set up in a portable laboratory at the site.

3) Analysis performed at an off-site analytical laboratory using EPA Contract Laboratory Program (CLP) or equivalent methods, but without the validation or documentation procedures required for CLP.

4) CLP routine analytical services and complete data reporting packages.

5) Analysis by non-standard methods (to achieve very low detection limits or measure a specific parameter not included in standard methods).

Stormwater samples are generally analyzed using Levels I, II, or III. Levels IV and V are not used very often for stormwater projects because these levels are intended for situations requiring low detection limits and high confidence, such as human or ecological risk assessments or Superfund/MTCA investigations.

- Appropriate methods for the chemicals of concern: Chemicals of concern are the most significant contributors to human health or environmental risk and are generally the most toxic, mobile, persistent, and/or frequently occurring chemicals found at the site. Commonly occurring chemicals of concern in stormwater runoff include metals (cadmium, copper, lead, and zinc), PAHs, and organo-phosphate insecticides (e.g., diazinon and chloropyrifos). Other chemicals (e.g., organochlorine pesticides and PCBs) should be included if there is reason to believe they are present. Note that the potential toxicity of some metals in freshwater systems is affected by the hardness of the water; thus, water quality standards for cadmium, copper, chromium, lead, nickel, silver, and zinc are calculated based on water hardness. For this reason, total hardness should be measured if metals are measured at sites where fresh water quality standards may apply. Examples of Level V monitoring may include particle size distribution analysis and sample extraction methods for organics.

- Level of concern: This term refers to the chemical concentration that is of concern. Typically, state or federal water quality criteria for protection of aquatic life or human health are used as the default level of concern for water sample results, and sediment quality criteria are used as the level of concern for sediment sample results. For pollutants that do not have state or federal water or sediment quality standards, the Risk-based Concentration Table developed by EPA Region III (EPA 1994a,b) can be used as levels of concern for water and soil sample results.

- Required detection limit/practical quantification limit: The level of concern directly affects the data quality requirements because the sampling and analysis methods used must be accurate at the level of concern. Sampling variability is often difficult to control, especially in stormwater. The relative accuracy of most laboratory methods decreases as concentrations approach the detection limits. For these reasons, the practical quantification limit (5 to 10 times the detection limit) should be below the level of concern, if possible.

If the objective is to conduct a screening study to identify chemicals that appear to be present at levels of concern, consider analyzing for a wide range of constituents using analytical methods with low detection limits. An initial screening analysis can generally reduce the number of chemicals analyzed in subsequent studies by eliminating those that were detected below their corresponding levels of concern.

In cases where it is known that there is a high degree of correlation between the concentration of the target pollutant(s) and some other parameter (e.g., fine particles, TSS, total organic carbon), then it may be possible to use less costly monitoring approaches to track the substitute, or "proxy" parameter(s). Although this approach can introduce some uncertainty because it does not track the target pollutants, it is still worthy of consideration. If the correlations are known to be strong and the cost differences pronounced, this strategy may provide a way to obtain much more data (i.e., more frequent observations during more storm events and/or at more locations). Such improvements in data quantity could more than offset the uncertainties introduced by imperfect correlations.

There are many precedents for using proxy parameters as indicators. For example, *E. coli* or fecal coliform are typically used as indicators for pathogens and fecal contamination. Total organic carbon and COD are sometimes used as proxies for biochemical oxygen demand (BOD). Turbidity is commonly used as a proxy for suspended solids, which in turn, is sometimes used as a proxy for other pollutants of concern (e.g., metals, PAHs).

In many BMP monitoring programs, there are opportunities to obtain additional information at little or no incremental cost (e.g., temperature or pH data). Such information may turn out to be valuable to the overall stormwater program at some time in the future and/or to others programs.

4.2 Sampling Location

The location of a permanent sampling station is probably the most critical factor in a monitoring network that collects water quality data. If the samples collected are not representative of the flow conditions, the frequency of sampling and data interpretation approach are inconsequential. The representativeness of a water quality sample is a function of the uniformity of the sample concentrations in a flow path's cross-sectional area. Wherever the concentration of a water quality variable is independent of depth and lateral location in a flow path's cross section, the flow path at that point is completely mixed and could serve as a desirable sampling location (Saunders 1983). Extensive discussion on this subject can be found in Fischer et al. (1979).

To assess BMP performance, sampling locations typically include an upstream and downstream location and, in some cases, one or more intermediate locations within the BMP or the BMP system, as described below.

4.2.1 Upstream

Monitoring stations established upstream of a BMP can give results that reveal the influent concentration or load of pollutants before they flow through the BMP. Upstream water quality is indicative of concentrations and pollutant loads that would be observed downstream if no BMP were implemented. It is important to monitor only waters that flow into the BMP to be able to use the resultant data to compare upstream water quality with downstream locations. Upstream monitoring locations can also be useful to determine bypass water quality. Where bypass is present, accurate flow measurement is highly important. Where sufficient funds are available and the physical layout of the control structures allow, bypass and flow to the BMP should be monitored directly. In situations where direct measurement is not practical, modeling of bypass flows can be substituted, particularly where the hydraulics of the bypass structure are well known or can be calibrated to flow rates. Typically, a mass balance approach is used to model bypass flow rates and volumes.

Upstream monitoring stations should be located far enough away from the BMP to ensure that samples are independent of the BMP. Immediately upstream from a BMP, contributing runoff could be affected by backflow, slope, vegetation, etc.

4.2.2 Downstream

Monitoring stations established downstream of a BMP are used to monitor water quality of flows that are treated by the BMP. Downstream monitoring is essential for establishing:

- Whether the BMP provides a measurable and statistically significant change in water quality.
- Whether the BMP provides effluent of sufficient quality to meet water quality criteria.
- Whether the BMP’s effluent concentrations are comparable to similar BMPs to assess whether the BMP is achieving typical effluent water quality.

Monitoring stations should be located immediately downstream of the BMP so that BMP effluent is sampled before it is introduced into the receiving waters or is exposed to factors that may affect constituent concentrations. Where bypass is present and one wants to understand the efficiency of the BMP system, it is important to monitor water quality of the bypass flows prior to mixing with the effluent from the BMP. In many cases, BMP influent data can be used to estimate bypass water quality; however, accurate estimates of bypass flow rates and/or volumes from monitoring or flow modeling will still be needed. In some cases, bypass flows may be very difficult to separate from treated effluent (e.g., in hydrodynamic devices).

4.2.3 Intermediate Locations

BMPs are sometimes designed as a group of devices or chambers that target specific processes. For example, a media filter might have a settling chamber to quickly remove large settleable solids before flowing into the filter media chamber. A treatment train approach is sometimes taken to combine various practices in order to maximize removal of specific constituents. Intermediate monitoring locations in the interior of the BMP are useful for investigating how various sections of the facility are working. Monitoring stations are also useful in between treatment train practices to assess effectiveness of each individual component in addition to monitoring upstream/downstream stations to determine overall BMP efficiency. (In this case, the intermediate monitoring location is the effluent from the upstream BMP and the influent to the downstream BMP.)

For interior monitoring, such as in the middle of a wetland or detention pond, stations should be established in a location that is representative of the facility. When selecting intermediate monitoring locations, it is important to have a clear understanding of the hydraulic/hydrologic features of the system to avoid “dead zones”. For example, monitoring within a wetland should be done in the middle section, where the slopes, vegetation, channel width, and so on are uniform and similar to the rest of the wetland, avoiding any microcosms of unique vegetation, basins, or slopes. Additionally, intermediate sampling location results have different implications, depending on whether the system processes operate as a plug flow reactor or a continuously stirred tank reactor. In the case of a system that operates more like a plug flow reactor, an intermediate sample location would represent the mid-point of the reactions.

To monitor in between treatment train practices, stations should be established to capture effluent from the upstream BMP or inflow to the downstream BMP, or both. Monitoring should not be conducted in a place where backflow or mixing occurrs, as these processes do not allow for isolated sampling of direct BMP discharge or inflow. During high flow conditions, this may be difficult because many BMPs overflow, reducing the distinction and separation between BMPs. Intermediate treatment train BMP monitoring stations need to be carefully evaluated to determine if samples taken during high flows are representative of water quality of flow between the BMPs and not backflow or some other phenomena.

Other intermediate monitoring locations sometimes associated with Low Impact Development (LID) studies that rely on infiltration may include soil moisture or groundwater monitoring at various depths. Similarly, some grass swale and buffer studies may incorporate monitoring at various distances along the flow path. Researchers must balance study complexity and cost associated with additional monitoring stations with the expected benefits of additional stations such as better characterizing the effectiveness of various treatment system components.

4.3 Water Quality Sample Collection Techniques

Regardless of whether manual or automated sampling techniques are used, it is critical to select sampling locations that are well mixed and will yield relatively homogenous samples (Clark et al. 2009). Basic guidance and references for grab sample and automated sample approaches follow.

4.3.1 Grab Samples

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. The results from a single grab sample generally are not sufficient to develop reliable estimates of the event mean concentration (EMC) for the pollutant 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. In such cases, the first flush may carry pollutants that accumulated in the collection system and paved surfaces during the dry period before the storm. 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. However, this strategy may be less effective in areas subject to numerous low-intensity, long duration storms with short inter-event times, because “first flush” effects are less obvious under such weather conditions.

- Some measurable parameters, such as temperature, pH, total residual chlorine, phenols, volatile organic compounds (VOCs), and bacteria transform or degrade so rapidly that compositing 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. Although automated VOC samplers have been used in the past, they are no longer recommended.)

- Some pollutants, such as oil and grease and total petroleum hydrocarbons, 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.)

To estimate EMCs or pollutant loads, a series of grab samples at short time intervals can be collected throughout the course of a storm event. There are several different approaches for obtaining information from a series of grab samples. One approach would be to analyze each grab sample individually. If the samples are analyzed individually, the results can be used to assess the rise and fall of pollutant concentrations during a storm and to estimate EMCs of pollutants. This approach can be particularly useful if the monitoring objective is to discern peak pollutant concentrations or peak loading rates for assessing short-term water quality impacts. Analyzing each grab separately adds significantly to laboratory costs; consequently, this approach is rarely used except when program objectives require detailed information about changes in constituent concentrations over the course of a storm.

4.3.2 Composite Samples

Another sampling approach is to combine appropriate portions of each grab sample to form a single composite sample for analysis, but this is generally impractical if there are more than a few stations to monitor. Moreover, manual monitoring can be more costly than automated monitoring if the monitoring program encompasses more than a few storm events. For these reasons, many monitoring programs have found that the use of automated monitoring equipment and methods are more appropriate for compiling composite samples than manual monitoring. If detecting peak concentrations or loading rates is not essential, composite sampling can be a more cost-effective approach for estimating EMCs and pollutant loads. A composite sample is a mixture of a number of individual sample "aliquots." The aliquots are collected at specific intervals of time or flow during a storm event and combined to form a single sample for laboratory analysis. Thus, the composite sample integrates the effects of many variations in stormwater quality that occur during a storm event. Composite samples are suitable for most typical stormwater quality parameters, but are unsuitable for parameters that transform rapidly (e.g., *E. coli*, residual chlorine, pH, VOCs) or adhere to container surfaces (e.g., oil and grease).

The two basic approaches for obtaining composite samples are referred to as time-proportional and flow-proportional. A time-proportional composite sample is prepared by collecting individual sample aliquots of equal volume at equal increments of time (e.g., every 20 minutes) during a storm event, and mixing the aliquots to form a single sample for laboratory analysis. Time-proportional samples do not account for variations in flow; pollutant concentrations in sample aliquots collected during the portion of the storm with lower flows are given the same "weight" as sample aliquots collected during higher flows. Consequently, time-proportional composite samples generally do not provide reliable estimates of EMCs or pollutant loads, unless the interval between sample aliquots is very brief and flow rates are relatively constant.

Flow-weighted composite samples are more suitable for estimating EMCs and pollutant loads. A flow-weighted composite sample can be collected in several ways (EPA 1992):

1) Constant Time: Volume Proportional to Flow Rate. Sample aliquots are collected at equal increments of time during a storm event and varying amounts of each aliquot are combined to form a single composite sample. The amount of water removed from each aliquot is proportional to the flow rate at the time the aliquot was collected. This type of composite sample can be collected using either manual or automated techniques.

2) Constant Time: Volume Proportional to Flow Volume Increment. Sample aliquots are collected at equal increments of time during a storm event and varying amounts from each aliquot are combined to form a single composite sample. The amount of water removed from each aliquot is proportional to the volume of flow since the preceding aliquot was collected. This type of compositing is generally used in conjunction with an automated monitoring system that includes a continuous flow measurement device. It can be used with manual sampling in conjunction with a continuous flow measurement device, but this combination is uncommon.

3) Constant Volume: Time Proportional to Flow Volume Increment. Sample aliquots of equal volume are taken at equal increments of flow volume (regardless of time) and combined to form a single composite sample. This type of compositing is generally used in conjunction with an automated monitoring system that includes a continuous flow measurement device.

Select the flow-weighted compositing method most suitable for the program based on the monitoring technique (manual or automated) and planned equipment. Compositing Methods 2 and 3 are more accurate than Method 1 because Methods 2 and 3 both use the total volume of flow based on continuous flow measurement to scale the sample volume. In contrast, Method 1 uses a single instantaneous rate measurement to estimate the flow over the entire sampling interval. However, for manual methods, compositing Method 1 is generally the most practical choice. If automated equipment is to be used, Method 3 is generally preferred because it minimizes the need for measuring and splitting samples, which are activities that can increase the chance for sample contamination. If automated methods will be used, the equipment manufacturer's specifications and instructions should be reviewed to select the compositing method most appropriate for that particular make and model.

Storm events affect stream flows for variable lengths of time depending on the storm duration and antecedent conditions and catchment characteristics. Runoff may persist for a period of a few hours to one or two days. This suggests runoff rarely persists long enough to be considered comparable to chronic exposure duration. Discrete sampling over the course of the storm event will provide concentration information that can be used to determine how long water quality criteria were exceeded during the storm. Alternatively, discrete samples can be composited on a time-weighted basis over time scales comparable to the acute and chronic water quality criteria exposure periods (one hour and four days, respectively). However, the latter would likely include dry-weather flows since few storms last four days. For catchments which are relatively small (a few acres), it is recommended that one or more one-hour composite samples be collected during the first few hours of flow by collecting and combining three or more grab samples.

Flow-weighted composite sampling can be used for comparison with water quality objectives (for example, if flow-weighted composites are collected to measure loads). However, it should be recognized that a flow-weighted sample contains more water from peak flows than from the initial part of the storm. Results from Santa Clara Valley Nonpoint Source Monitoring Program indicated that for a large watershed with significant suspended sediment concentrations (200 - 400 mg/L), peak total metals concentrations are generally 1.5 times the flow-weighted composite concentrations (WCC 1993). Results from monitoring a smaller, highly impervious industrial catchment with lower suspended sediment concentrations were more variable, and no conclusions could be drawn as to the relationship between flow-composite concentrations and grab samples due to difficulties in grab sampling runoff that only occurred during precipitation.

4.3.3 Automated Sampling

Automated monitoring involves sample collection using electronic or mechanical devices that do not require an operator to be on-site during actual stormwater sample collection. It is the preferred method for collecting flow-weighted composite samples. Automated monitoring is generally a better choice than manual monitoring at locations where workers could be exposed to inadequate oxygen, toxic or explosive gases, storm waves, and/or hazardous traffic conditions. Automated samplers can be set so that sampling operations are triggered when a pre-determined flow rate of storm runoff is detected. Conversely, manual monitoring relies on weather forecasts (and considerable judgment and good luck) to decide when to send crews to their monitoring stations. It is very difficult to predict when stormwater runoff is likely to begin; consequently, manual monitoring crews may arrive too early and spend considerable time waiting for a storm that begins later than predicted, or they may arrive too late and miss the "first flush" from a storm that began earlier than predicted. If the automated equipment is set to collect flow-weighted composite samples using the constant volume-time proportional to flow method, it reduces the need to measure samples for compositing.

If field-measured "indicator" parameters (e.g., turbidity, conductivity, dissolved oxygen, pH) are sufficient for meeting monitoring objectives, electronic sensors and data loggers may be useful.

Electronic sensors and data loggers can provide near-continuous measurements of indicator parameters at reasonable cost.

BMP monitoring can be an especially useful application for some automated systems (e.g., continuous flow recorders, auto samplers, continuous monitoring probes) for the following reasons:

- Automated systems can provide data covering virtually the entire volume of runoff that passes through the BMP (i.e., they are not likely to miss or leave out small events and the beginnings and ends of other events).

- Automated systems are well suited to providing data sets that are useful (recognizing that performance evaluations are generally based on the differences between inlet and outlet concentration data sets, both of which are inherently noisy).

- The information obtained from good performance monitoring programs can be very valuable by protecting against inappropriate BMP applications. Therefore, the cost of using automated systems is often justifiable.

4.3.3.1 Automated Sampling Equipment

An automated sampler is a programmable mechanical and electrical instrument capable of drawing a single grab sample, a series of grab samples, or a composited sample, in-situ. The basic components of an automated sampler are a programming unit capable of controlling sampling functions, a sample intake port and intake line, typically a peristaltic pump (although vacuum/compression pumps may also be used), a rotating controllable arm capable of delivering samples into sample containers and a housing capable of withstanding moisture and some degree of shock. Additionally, inexpensive first-flush sampling equipment for specific regulatory purposes is also now available.

An automated sampler can be programmed to collect a sample at a specific time, at a specific time interval, or on receipt of a signal from a flow meter or other signal (e.g., depth of flow, moisture, temperature). The sampler distributes individual samples into either a single bottle or into separate bottles which can be analyzed individually or composited. Some automated samplers offer multiple bottle configurations that can be tailored to program objectives.

Important features of automated samplers include:

- Portability

- Refrigeration

- Alternative power supplies

Exhibit 4-8. Programming an Automatic Sampler

Portable samplers are smaller than those designed for fixed-site use, facilitating installation in confined spaces. If a suitable confined space is not available or is undesirable (e.g., because of safety issues), the sampler can be housed in a secure shelter at the sampling site. Portable samplers can use a 12V DC battery power supply, solar battery, or AC power.

Several manufacturers produce automatic sampling equipment that can refrigerate samples as they are collected. For non-refrigerated samplers, ice may be added to the housing of some units to preserve collected samples at a temperature as close to 4°C as possible. The objective of this cooling is to inhibit pollutant transformation before the sample can be analyzed.

It is important to be aware that some common sampler heads do not function at subfreezing temperatures without retrofit. After-market heater and thermostats can be purchased to enable year round continuous monitoring in cold climates. Similarly, data logger failure due to cold temperatures can result in data loss.

In typical installations for BMP sampling, for each of the types of samplers described above, an intake line is bracketed to the channel bottom. The intake tubing should be mounted as unobtrusively as possible, to minimize disturbance of the site hydraulics. Generally, the optimum position for the intake is to the channel bottom. However, if high solids loadings are expected and potential deposition could occur, the intake can be mounted slightly higher on one side of the channel wall. Typically, a strainer is attached to the intake to prevent large particles and debris from entering the tubing. The strainer is usually installed so that it faces upstream, into the flow. This configuration minimizes the development of local turbulence that could affect representative sampling of constituents in the particulate phase.

Two types of pumps are incorporated into automated samplers for typical water quality sampling: peristaltic and vacuum/compressor.

Peristaltic Pump

A peristaltic pump creates a vacuum by compressing a flexible tube with a rotating roller, drawing a sample to the pump that is then pushed out of the pump. Field experience with peristaltic pumps has shown that their reliability in drawing a consistent sample volume is greatly reduced as the static suction head (i.e., distance between the flow stream surface and the sampler) increases. It may be possible to increase the efficiency of these samplers by placing the pump closer to the sample source, reducing the suction head. In addition, changing the tubing from the peristaltic pump on a regular basis will improve consistency. In general, the sampler itself should be installed no more than 6 meters (20 feet), and preferably less, above the channel bottom. If the sampler is to be installed at greater than 20 feet above the channel invert, it may be necessary to use a remote pump that is placed closer to the flow stream to ensure reliable sample collection.

The degree to which sampler lift affects the concentration of TSS and other pollutant parameters, especially coarser materials, is not well known. That is, the mean transport velocity achieved by the peristaltic pump is sufficient to draw suspended solids; however, the pulsed nature of the flow may allow suspended solids to settle back down through the pump tubing during transport. There have been improvements in capabilities of pumps for automated samplers over the past five years enabling collection of larger/heavier particles with fewer problems. In work performed by the USGS (FHWA 2001), it was found that suspended solids concentrations did not vary with pumping height (0 to 24 ft); however, sample volumes delivered to sample bottles did vary from sample to sample at high lift heights for some of the older sampler models.

Another concern with peristaltic pumps is their incompatibility with Teflon®-lined tubing in the pump assembly. Compression of the intake tubing by the rollers tends to create stress cracks and small recesses in the lining where particles can accumulate. Under these circumstances, some pollutant concentrations could be underestimated and the cross-contamination of samples can occur. Although Teflon®-lined tubing is preferable because it reduces the potential loss of pollutants through surface interactions, this advantage cannot be accommodated with a peristaltic pump.

Vacuum/Compressor Pump

A vacuum/compressor pump draws a sample by creating a vacuum. Although less commonly present in currently available equipment, this type of pump can create a higher transport velocity in the intake tube and provide more steady and uniform discharge than a peristaltic pump. However, the higher intake velocity can scour sediments in the channel near the sampler intake, resulting in disproportionately high concentrations of suspended solids.

After a sampler is installed, it must be programmed to collect the desired sample size. Calibration of peristaltic pumps is achieved by one of two methods: automatic or timed. In automatic calibration, the actual volume of sample drawn is measured using a fluid sensor located at the pump and the known pump speed. In timed calibration, the volume is determined from the number of revolutions of the peristaltic pump and the time taken for the sample to travel from its source to the sample container. Calibration by this latter method is site specific and incorporates the pump speed, the head (vertical distance above the sample source), and the length and diameter of the intake tubing. The Manning and Epic samplers, which employ vacuum pumps, permit adjustment for specific sample volumes via a fluid level device in a chamber. This chamber can cause sample cross-contamination, as it cannot be flushed like the tubing can.

4.3.3.2 In-Situ Water Quality Devices

The concentration of most pollutants in stormwater runoff is likely to vary significantly over the course of a given storm event. Some of this variability can be captured through the collection of multiple samples. The ideal data set would contain not just multiple samples, but also a continuous record of constituent concentrations throughout a storm, capturing both the timing and magnitude of the variations in concentration. Given the availability of other continuous data, this approach might allow better correlation with potential causative factors. Unfortunately, the laboratory costs for even a near-continuous data set would be prohibitive. USGS determined that between 12 and 16 individual samples resulted in a mean that was within 10 to 20 percent of the actual event mean concentration (FHWA 2001). In-situ monitoring devices offer a possible solution to obtaining a continuous record of water quality; however, at this time, they are only practical for a limited set of parameters.

In-situ water quality probes have been adapted from equipment developed for the manufacturing and water supply/wastewater industries. In-situ water quality monitors attempt to provide the desirable near-continuous data set described above at a relatively low cost, eliminating (or reducing) the need for analysis of samples in the laboratory.

In general, water quality monitors are electronic devices that measure the magnitude or concentration of certain specific target constituents through various types of sensors. Discrete measurements can be made at one minute or less intervals. 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 to detect and measure the following physical and chemical parameters are currently available for practical use in the field:

Physical Parameters

- Temperature
- Turbidity

Chemical Parameters

- pH
- Oxidation-reduction potential (redox)
- Conductivity
- Dissolved oxygen
- Salinity
- Nitrate (not currently recommended)
- Ammonia (not currently recommended for remote/unattended operation)
- Resistivity
- Specific conductance
- Ammonium

There are some potential probes for heavy metals, but given the complexities associated with highly variable solids concentrations and other factors, studies have found that they are not practical for field application (FHWA 2001). Instruments can be configured to measure the concentrations of several of these parameters simultaneously (i.e., multi-parameter probes) and provide data logging and PC compatibility.

In many cases, the electrochemical reaction that drives a probe's response is sensitive to changes in temperature, pH, or atmospheric pressure. Where appropriate, monitors are designed to simultaneously measure these associated properties. Data on the target constituent are then corrected through a mathematical routine built into the probe's microprocessor (e.g., dissolved oxygen probes are compensated for temperature and atmospheric pressure, pH probes for temperature. and ammonia probes for pH), or are adjusted in a spreadsheet after downloading to a personal computer. As of publication of this manual, nitrate probes are not recommended, but improvements in technology may occur in the future. Similarly, ammonia probes currently require frequent calibration, which limits their use from a practical perspective.

Despite the advantage of these instruments for measuring near-continuous data, they 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. Therefore, these instruments should always be cleaned and calibrated before use. Because water quality probes are designed to operate while submerged in water, exposure of the electrochemically active probe surface to air should be minimized.

4.3.3.3 Remote Communication with Automatic Equipment

The ability to remotely access the memory and programming functions of automated samplers is a highly desirable feature for large stormwater sampling networks. Although this feature increases the capital cost for a system, it can greatly reduce the expertise and training necessary for field crews because many of the technical aspects of equipment set-up and shut-down can be conducted by a system supervisor remotely.

Currently, modem communication is an available option to most commercially-produced automated samplers. However, there are several common drawbacks that may be encountered with the communication systems currently offered by manufacturers:

- Full access to all sampler programming features may be limited. This means that trained field crews may still be necessary to ensure sampler programming is correct.
- For multiple instrument systems (i.e., separate flow meter and automated sampler), communication and complete operation of both components through one modem system is generally not available.

Remote communication for both samplers and flow meters is a rapidly advancing technology. Stormwater monitoring applications should continue to benefit from advances made in wastewater and drinking water monitoring applications. Some of the newer cellular modems and software now allow for Supervisory Control and Data Acquisition (SCADA) of automatic samplers, allowing for improved remote programming, monitoring of sampler status and review of data as it is collected.

4.3.4 Manual Sampling

Manual monitoring involves sample collection and flow measurement by personnel using hand-operated equipment such as a bailer or bottle. For a monitoring program that is modest in scope (i.e., relatively few sampling sites and storm events), manual methods for obtaining grab and composite samples may be preferable to those employing automated equipment. For programs that require monitoring large streams, manual methods may be needed to collect cross-section composites. The principal advantages to manual sampling are its relatively low capital cost and high degree of flexibility. In addition to the capital outlay required for the purchase of automated samplers, other costs, such as installation, training personnel to use the samplers correctly, and field maintenance and operations (e.g., replacing batteries, interrogating data loggers, retrieving and cleaning sample jars) can be substantial.

Manual sampling is usually preferred under the following circumstances:

- When available resources for equipment purchase/installation (e.g., funds, personnel, time) are very constrained and/or there is not the political will to invest in a program.
- When the target pollutants do not lend themselves to automated sampling or analysis (e.g., oil and grease, volatile organic compounds, bacteria).
- When the physical setting of the BMP does not allow the use of automated systems.

However, manual monitoring may not be feasible if:

- Monitoring personnel are not available after normal working hours.
- Monitoring personnel have strict job descriptions that do not include sampling.
- The organization's insurance policy doesn't cover stormwater monitoring activities.
- Managers and monitoring personnel are not able to deal with sick days, vacations, and competing priorities.

Manual sampling is generally less practical than automated monitoring for large-scale programs (e.g., monitoring programs involving large numbers of sites or sampling events over multiple years). It is difficult to collect true flow-weighted composites using manual methods. Under these circumstances, labor costs and logistical problems can far outstrip those associated with automated equipment. For the same reason, manual sampling is seldom practiced if specific program objectives require that samples be composited over the entire duration of a storm, which is recommended for BMP monitoring.

Manual equipment can be used in collecting grab samples, composite samples, or both, as described below.

4.3.4.1 Manual Grab Sampling Equipment

Manual sampling techniques and equipment have been reviewed in detail by Stenstrom and Strecker (1993). 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.

As described earlier, the concentrations of suspended constituents tend to stratify within the flow stream depending on their specific gravity and the degree to which flow is mixed by turbulence. Use of a discrete-depth sampler for multiple samples should be considered when constituents lighter or heavier than water are targeted, or if the flow is too deep and/or not well mixed enough to be sampled in its entirety (Martin et al. 1992). However, stormwater BMPs often drain relatively small catchments and contain fairly shallow flows. Collection of depth-integrated samples at these sites is not usually performed.

Given the extremely low detection limits that laboratory analytical instruments can achieve, leaching of water quality constituents from the surface of a bailing device or sample bottle can affect water quality results. Sample bottles of the appropriate composition for each parameter are usually available from the analytical laboratory. Depending upon the pollutant to be analyzed, 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. (Method blanks are an important quality control tool that can help determine whether leaching of materials from sampling equipment is an issue.)

4.3.4.2 Manual Composite Sampling Equipment

If grab samples will be composited based on flow rate (i.e., grab samples collected during high flow contribute more to the composited sample than those collected during low flow), some receptacle for storing the individual grab samples prior to compositing will be required. The use of polyethylene jugs, or polyethylene cubes with screw-on caps manufactured for shipping chemicals, is recommended. These can be shaken to remix the sample prior to pouring out the required volume. The volume required from each receptacle can be measured in a graduated cylinder and poured into a bucket for compositing. Both the cylinder and the bucket should be made from a Teflon™-coated plastic or high-density polyethylene and should be cleaned prior to use. Be aware that every transfer of sample from one container to another risks losing sample volume and pollutants; thereore, care should be taken during sample transfers. Sample splitting is complex and prone to error. References to ensure good sampling procedures are provided in Exhbit 4-9.

Exhibit 4-9. Supplemental References Regarding Sample Spliting

Capel et al. 1995. *Precision of a splitting device for water samples.* USGS Open-File Report 95-293, 6 p. http://pubs.er.usgs.gov/usgspubs/ofr/ofr95293

Capel et al.1996. *Evaluation of selected information on splitting devices for water samples.* U.S. Geological Survey Water-Resources Investigations Report 95-4141. 103 p.

Horowitz et al. 2001. *Selected laboratory evaluations of the whole-water sample-splitting capabilities of a prototype fourteen-liter Teflon® churn splitter*. U.S. Geological Survey Open-File Report 01-386. http://pubs.usgs.gov/of/2001/ofr01-386/

Kayhanian et al. 2008. Utility *of suspended solid measurements for storm-water runoff treatment*. Journal of Environmental Engineering, Volume 134, Issue 9. 712-721 p.

4.4 Sediment Sampling

Many constituents either settle out of the water column or prefer not to be in the water column (due to hydrophobicity) and become incorporated in the sediment. Sediment can store significant amounts of certain constituents, such as benzene, toluene, ethylbenzene, and xylenes (BTEX), PCBs, metals, and microbes. During high flows, these sediments are stirred up and can release potentially high concentrations of accumulated constituents. Many BMPs are designed to remove the sediment from runoff, theoretically removing the associated constituents as well.

Sediment sampling can determine concentrations of constituents not necessarily found through water column monitoring. Sediments can be sampled upstream and downstream of BMPs, as well as internal to the BMP, to assess removal and effluent efficiencies as well as internal accumulation of sediment and associated constituents.

When sampling sediment from the creek bed or internal to the BMP (e.g., sampling the filter media or detention pond bottom sediments), sediments should be collected minimizing disturbance or resuspension of the sediment bed so that the original settled material is captured in the sample apparatus. Depth of sediment sample should also be noted as constituent concentrations can vary with depth.

Bedload sampling can be conducted to sample sand, silt, gravel or rock debris carried by channel on or immediately above its bed. Bedload materials have particle sizes or a density that do not allow movement far above or for long distances out of contact with the streambed. Bedload samplers can either be hand-held or cable-suspended. Standard sampler bags come with a 250 micron mesh size (ASTM specs) made out of nylon for abrasion resistance. Bags can also be provided with 125, 500, and 1000 micron openings, if needed. Several different types of bedload samplers are available. See ASCE (2007), USGS (2005), the Federal Interagency Sedimentation Project (http://fisp.wes.army.mil/), and vendor websites for more information on features of these samplers.

4.5 Soil (Infiltration Media) Sampling

As infiltration-oriented stormwater management practices are increasingly advocated, collection of soil and infiltration media samples become increasingly important. This type of sampling is helpful in assessing depth and extent of pollutant accumulation in soil layers and relationship of pollutants in groundwater or the vadose zone to accumulated pollutants in the infiltration media (Clark, Pitt, and Field 2009). Additionally, documentation of soil chemical properties is important in identification of factors influencing BMP performance. For example, microbial groundwater contamination from infiltrated urban runoff is influenced by soil chemical properties that promote adsorption and retention of microbial organisms (Clark et al. 2006; Clark, Pitt, and Field 2009). Other soil characteristics influence infiltration rates and nutrient loading to groundwater. For example, compost-amended soils may improve infiltration rates, but may also contribute to nutrient loading to groundwater if not carefully selected (Pitt et al. 1999; Clark, Pitt, and Field 2009.). Sample collection from infiltration media is important to help further the understanding of the lifespan and maintenance requirements of infiltration devices.

Site soil evaluations should include several components, including infiltration measurements, soil density, texture, and moisture determinations. Soil chemical measurements should include a variety of parameters, including soil texture (i.e., percent of sand, silt, and clay), organic matter, cation exchange capacity and general nutrients (Pitt 2009). Organic carbon content and phosphorus index ("P Index") are also useful. Chapter 8 provides additional infiltration-related monitoring information.

4.6 Groundwater Sampling

A discussion of groundwater sampling is beyond the scope of the current monitoring manual; however, it is increasingly important for LID and infiltration-oriented BMPs. The references listed in Exhibit 4-10 are good resources for guidance with regard to groundwater sampling.

Exhibit 4-10. Supplemental Groundwater Monitoring Resources

Bouwer, H. 1978. *Groundwater Hydrology*. McGraw-Hill Book Company.

Brown, C. J., Scorca, M. P., Stockar, G. G., Stumm, F., and H.F. Ku. 1997. *Urbanization and recharge in the vicinity of East Meadow Brook, Nassau County, New York*. U.S. Geological Survey WRI 96-4289. http://pubs.er.usgs.gov/usgspubs/wri/wri964289

Freeze, R.A and J.A. Cherry. 1979. *Groundwater*, Prentice-Hall, Inc.

Granato, G.E. and K.P Smith. 1999. *Robowell: An automated process for monitoring ground water quality using established sampling protocols*. Ground Water Monitoring and Remediation, Volume 19, Number 4. 81-89 p. http://ma.water.usgs.gov/automon/rwgwmr.pdf

Granato, G.E. and K.P. Smith. 2000. *Automated Groundwater Monitoring System and Method: Washington D.C.* U.S. Government Patent and Trademark Office, United States Patent 6,021,664. 31 p. http://ma.water.usgs.gov/automon/US6021664.pdf

Pitt, R., Clark, S. and K. Parmer. 1994. *Potential for Groundwater Contamination from Intentional and Nonintentional Stormwater Infiltration*. EPA/600/R-94/051 (NTIS 94-165 354). Environmental Protection Agency, Cincinnati, OH. http://www.p2pays.org/ref/07/06744.pdf

Herzog, B.L., Pennio, J.D. and G.L. Nielsen. 1991. *Ground-Water Sampling*. In *Practical Handbook of Ground-Water Monitoring*. Editor D.M., Nielsen, Chelsea, Michigan, Lewis Publishers, Inc.

Koterba, M.T., Wilde, F.D., and W.W. Lapham. 1995. *Ground-water data-collection protocols and procedures for the National Water-Quality Assessment Program--Collection and documentation of water-quality samples and related data*. U.S. Geological Survey Open-File Report 95-399. http://pubs.usgs.gov/of/1995/ofr-95-399/

Ku, H.F. and D. L. Simmons. 1986. *Effect of urban stormwater runoff on ground water beneath recharge basins on Long Island, New York: 1986.* WRI 85-4088. http://pubs.er.usgs.gov/usgspubs/wri/wri854088

Ku, H.F. and D.B. Aaronson. 1992. *Rates of water movement through the floors of selected stormwater basins in Nassau County, Long Island, New York*. U.S. Geological Survey WRI 91-4012. http://pubs.er.usgs.gov/usgspubs/wri/wri914012

Wilde, F. 1994. *Geochemistry and Factors Affecting Ground-Water Quality at Three Storm-Water- Management Sites in Maryland. Department of Natural Resources*, Maryland Geological Survey, Report of Investigations No. 59.

Zhou, Y. 1996. *Sampling frequency for monitoring the actual state of ground water systems*. Journal of Hydrology, Volume 180. 301-318 p.

4.7 QA/QC for Water Quality Sampling

4.7.1 Sampling Methods

Proper sampling methods are essential in conducting a BMP monitoring program in order to ensure resulting data are meaningful and representative of the water and other media being processed by the BMP. Sampling methodologies and techniques that maintain and confirm the integrity of the sample are discussed below.

4.7.2 Grab Sample Collection Techniques

During moderate flow events, grab samples can be collected at some stations simply by approaching the water to be sampled and directly filling up the bottles, being careful not to lose any preservative already contained in the bottle. It is important also to be aware of surface conditions of the sampled water body, avoiding layers of algae and debris and areas of dense vegetation if possible. The bottle cap should be handled carefully, making sure not to introduce any extraneous dirt, water, debris, or vegetation while filling the bottle; bottle caps should not be placed on the ground facing downward. Sample labels should be placed on bottles, not bottle caps.

Low flow events may not provide sufficient flows to allow filling of bottles directly. In this case, sample collectors may be used to collect the low flow runoff and transfer the water into the sample bottles. These sample collectors are typically cup- to bucket-sized containers with a wide mouth and no neck, allowing the collector to be placed close to the bottom surface of the flow path and then filled with the small depth of flow. Sample collectors must be compatible in material with the sample bottles and the constituents to be analyzed. Sample collectors made of stainless steel, Teflon® or glass could be considered after investigating the compatibility of these materials with each constituent to be analyzed. After each sample bottle has been filled, and before the next monitoring site is to be sampled, the sample collector should be rinsed thoroughly with deionized water to prevent cross-contamination between sites. At least four rinses with deionized water are necessary, followed by filling the sample collector several times with new monitoring site runoff before finally using the collector to fill the sample bottles.

During high flow events, runoff may be unsafe to approach directly to collect the sample. Modified sample collectors can be designed to allow remote sampling. Many stainless steel buckets or cookware (asparagus cookers) have handles to which ropes may be tied at a length that allows the sample collector to be lowered into the runoff and raised back up after filling with water. These sample collectors with rope are ideal to use if sampling a creek from a bridge or sampling an outfall from a creek bank. In addition, modified sample collectors will work well to sample runoff in a manhole, eliminating the need to enter the confined space during higher flows. The advantage of the rope-and-bucket device is that a significant length of rope can be attached to the sample bucket to allow for sampling from great heights, yet the rope can be coiled and stored compactly. If a sturdier sampling device is needed, sample collectors may be attached to a pole using tape or rope and lowered into the runoff. Again, cross-contamination between sample sites should be prevented by rinsing the sampling collector with deionized water and new sample water several times.

4.7.3 Contamination/Blanks

Control over sample contamination is critical when attempting to measure concentrations of compounds at the parts-per-billion level. Contamination can be introduced either during the bottle/equipment preparation steps or during the sample collection, transport, or analysis steps. Control over all of these steps can be achieved through the use of standardized equipment cleaning procedures, clean sampling procedures, and clean laboratory reagents. The level of contamination introduced during each of these steps is determined by analysis of different types of blank samples. Each of these different types of blanks is described below:

- Method Blanks are prepared by the laboratory by analysis of clean Type II reagent water. They are used to determine the level of contamination introduced by the reagents and laboratory processing.

- Source Solution Blanks are determined by analysis of the deionized or Type II reagent water used to prepare the other blanks. The source solution blank is used to account for contamination introduced by the deionized water when evaluating the other blanks.

- Bottle Blanks are prepared by filling a clean bottle with source solution water and measuring the solution concentration. Bottle blanks include contamination introduced by the source solution water and sample containers. By subtracting the source solution blank result, the amount of contamination introduced by the sample containers can be determined.

- Travel Blanks are prepared by filling a sample container in the laboratory with Type II reagent water and shipping the filled water along with the empty sample containers to the site. The travel blank is shipped back with the samples and analyzed like a sample. The bottle blank result can be subtracted from the travel blank to account for contamination introduced during transport from the laboratory to the field and back to the laboratory.

- Equipment Blanks are usually prepared in the laboratory after cleaning the sampling equipment. These blanks can be used to account for sample contamination introduced by the sampling equipment, if the bottle blank results are first subtracted.

- Field Blanks account for all of the above sources of contamination. Field blanks are prepared in the field after cleaning the equipment and sampling Type II reagent water with the equipment. They include sources of contamination introduced by reagent water, sampling equipment, containers, handling, preservation, and analysis. In general, field blanks should be performed prior to or during the sample collection. Because the field blank is an overall measure of all sources of contamination, it is used to determine if there are any blank problems. If problems are encountered with the field blank, then the other components of the sampling process should be evaluated by preparation of other blanks in order to identify and eliminate the specific problem.

EPA's recent guidance on the use of clean and ultra-clean sampling procedures for the collection of low-level metals samples (EPA 1993a,b) should be considered to ensure bottles and equipment are cleaned properly and samples are collected with as little contamination as possible. While ultra-clean techniques throughout are likely not necessary for stormwater runoff samples, some of the laboratory procedures should be employed. For example, metals levels in highway runoff are typically much greater than introduced errors associated with in-field clean sampling techniques. These techniques are typically employed in receiving waters where their applicability is more relevant.

4.7.4 Reconnaissance and Preparations

Reconnaissance and preparation is an important component of any field sampling program. Proper reconnaissance will help field operations run smoothly and ensure field personnel are familiar with the sampling locations. During the planning stage, a site visit should be performed by the field personnel, prior to conducting sampling. The purpose of the site visit is to locate access points where a sample can be taken and confirm that the sampling strategy is appropriate. Because of the transient nature of meteorological events, it is possible sites may need to be sampled in the dark. For this reason, the actual persons involved in the field sampling should visit the site during reconnaissance as a complement to a training program for the monitoring effort.

The training program should include:

- A discussion of what the programs goals are and why their efforts are important.
- Familiarization with the site.
- Training on the use and operation of the equipment.
- Familiarization with field mobilization, sampling, and demobilization procedures.
- Health and safety requirements.
- QA/QC procedures.

4.7.4.1 Laboratory Coordination

Coordination with the laboratory is a critical step in the planning and sampling process. The laboratory should be made aware of specific project requirements such as number of samples, required laboratory performance objectives, approximate date and time of sampling (if known), required QA/QC samples, reporting requirements, and if and when containers or ice chests will be required. Laboratory personnel should be involved early in the process so they can provide feedback on methods and performance standards during the planning phase. For example, in cold climates where deicers are used, chlorides can significantly affect detect limits for nutrients; so communicate with the lab on this type of factor. Notifying the laboratory that stormwater sampling is planned is also important to allow the laboratory to plan for off-hours sample delivery and to set-up any analysis with short holding times.

4.7.4.2 Sample Containers/Preservation/Holding Times

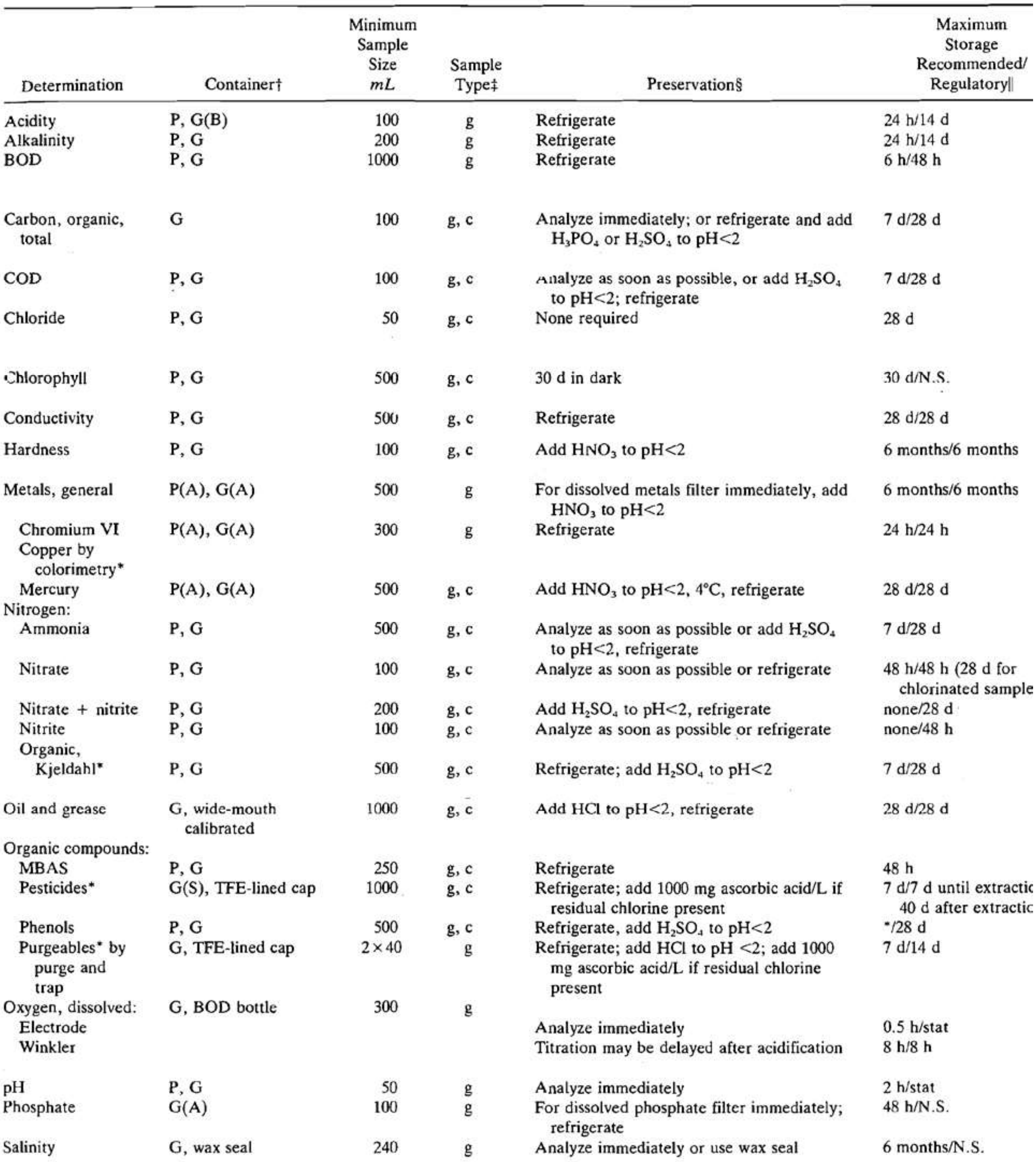
EPA recommends that samples be collected and stored in specific types of sample container materials (e.g., plastic, glass, Teflon®). For analysis of certain parameters, addition of specific chemical preservatives is recommended to prolong the stability of the constituents during storage. Federal Register 40 CFR 136.3 outlines recommended sample containers, preservatives, and maximum recommended holding times for constituents. Exhibit 4-11 summarizes container types, holding times, and other requirements for various analytes. Sample holding times should be compared to the recommended maximum holding times listed in the Federal Register. Laboratory quality control sample data should be compared to target detection limits as well as precision and accuracy goals and qualified specified in Quality Assurance Project Plans (QAPPs).

If composite sampling procedures are to be used to collect one large sample that will be subsampled into smaller containers, the composite sample bottle should be compatible with all of the constituents to be subsampled. In general, the use of glass containers will allow subsampling for most parameters (with the exception of fluoride).

Sample volumes necessary for the requested analysis should be confirmed with the laboratory prior to sample collection. Extra sample volume should be collected for field and laboratory QA/QC samples. As a general guide, if one station is to be used for both field and laboratory QA/QC measurements, four times the normal volume of water should be collected.

Exhibit 4-11. Summary of Special Sampling or Handling Requirements[*]

(Source: Standard Methods for the Examination of Water & Wastewater, APHA 2005)



Determination	Container†	Minimum Sample Size *mL*	Sample Type‡	Preservation§	Maximum Storage Recommended/ Regulatory‖
Acidity	P, G(B)	100	g	Refrigerate	24 h/14 d
Alkalinity	P, G	200	g	Refrigerate	24 h/14 d
BOD	P, G	1000	g	Refrigerate	6 h/48 h
Carbon, organic, total	G	100	g, c	Analyze immediately; or refrigerate and add H_3PO_4 or H_2SO_4 to pH<2	7 d/28 d
COD	P, G	100	g, c	Analyze as soon as possible, or add H_2SO_4 to pH<2; refrigerate	7 d/28 d
Chloride	P, G	50	g, c	None required	28 d
Chlorophyll	P, G	500	g, c	30 d in dark	30 d/N.S.
Conductivity	P, G	500	g, c	Refrigerate	28 d/28 d
Hardness	P, G	100	g, c	Add HNO_3 to pH<2	6 months/6 months
Metals, general	P(A), G(A)	500	g	For dissolved metals filter immediately, add HNO_3 to pH<2	6 months/6 months
Chromium VI	P(A), G(A)	300	g	Refrigerate	24 h/24 h
Copper by colorimetry*					
Mercury	P(A), G(A)	500	g, c	Add HNO_3 to pH<2, 4°C, refrigerate	28 d/28 d
Nitrogen:					
Ammonia	P, G	500	g, c	Analyze as soon as possible or add H_2SO_4 to pH<2, refrigerate	7 d/28 d
Nitrate	P, G	100	g, c	Analyze as soon as possible or refrigerate	48 h/48 h (28 d for chlorinated sample
Nitrate + nitrite	P, G	200	g, c	Add H_2SO_4 to pH<2, refrigerate	none/28 d
Nitrite	P, G	100	g, c	Analyze as soon as possible or refrigerate	none/48 h
Organic, Kjeldahl*	P, G	500	g, c	Refrigerate; add H_2SO_4 to pH<2	7 d/28 d
Oil and grease	G, wide-mouth calibrated	1000	g, c	Add HCl to pH<2, refrigerate	28 d/28 d
Organic compounds:					
MBAS	P, G	250	g, c	Refrigerate	48 h
Pesticides*	G(S), TFE-lined cap	1000	g, c	Refrigerate; add 1000 mg ascorbic acid/L if residual chlorine present	7 d/7 d until extractic 40 d after extractic
Phenols	P, G	500	g, c	Refrigerate, add H_2SO_4 to pH<2	*/28 d
Purgeables* by purge and trap	G, TFE-lined cap	2×40	g	Refrigerate; add HCl to pH <2; add 1000 mg ascorbic acid/L if residual chlorine present	7 d/14 d
Oxygen, dissolved:	G, BOD bottle	300	g		
Electrode				Analyze immediately	0.5 h/stat
Winkler				Titration may be delayed after acidification	8 h/8 h
pH	P, G	50	g	Analyze immediately	2 h/stat
Phosphate	G(A)	100	g	For dissolved phosphate filter immediately; refrigerate	48 h/N.S.
Salinity	G, wax seal	240	g	Analyze immediately or use wax seal	6 months/N.S.

Solids	P, G	200	g, c	Refrigerate	7 d/2–7 d; see cited reference
Sulfate	P, G	100	g, c	Refrigerate	28 d/28 d
Sulfide	P, G	100	g, c	Refrigerate; add 4 drops 2*N* zinc acetate/100 mL; add NaOH to pH>9	28 d/7 d
Temperature	P, G	—	g	Analyze immediately	stat/stat
Turbidity	P, G	100	g, c	Analyze same day; store in dark up to 24 h, refrigerate	24 h/48 h

* See text for additional details. For determinations not listed, use glass or plastic containers; preferably refrigerate during storage and analyze as soon as possible.

† P = plastic (polyethylene or equivalent); G = glass; G(A) or P(A) = rinsed with 1 + 1 HNO_3; G(B) = glass, borosilicate; G(S) = glass, rinsed with organic solvents or baked.

‡ g = grab; c = composite.

§ Refrigerate = storage at 4°C, in the dark.

‖ Environmental Protection Agency, Rules and Regulations. 40 CFR Parts 100–149, July 1, 1992. See this citation for possible differences regarding container and preservation requirements. N.S. = not stated in cited reference; stat = no storage allowed; analyze immediately.

\# If sample is chlorinated, see text for pretreatment.

4.8 Field QA/QC Procedures

Listed below are the recommended quality control samples and field procedures.

- Field Blanks: Field blanks should be prepared at least once by each field sampling team to prevent or reduce contamination introduced by the sampling process. It is recommended that field blanks be routinely prepared and analyzed with each sampling event. In addition, it is desirable to prepare field blanks prior to the actual sampling event as a check on procedures. This will ensure field-contaminated samples are not analyzed. Additional field blanks should be prepared if sampling personnel, equipment, or procedures change.

- Field Duplicate Samples: Field duplicate samples should be collected at a frequency of 5 percent or a minimum of one per event, whichever is greater. Field duplicate samples are used to provide a measure of the representativeness of the sampling and analysis procedures. These types of duplicates are recommended, but often not collected due to expense.

- Field Sample Volumes: Sufficient sample volumes need to be collected to enable the required laboratory QA/QC analysis to be conducted. In general, one station should be targeted for extra sample volume collection and identified on the chain-of-custody as the laboratory QA/QC station. If possible, this station should be the one where the data quality is most critical.

- Chain of Custody: All sample custody and transfer procedures should be based on EPA-recommended procedures. These procedures emphasize careful documentation of sample collection, labeling, and transfer procedures. Pre-formatted chain-of-custody forms should be used to document the transfer of samples to the laboratory and the analysis to be conducted on each bottle.

4.9 Laboratory QA/QC Procedures

Listed below are key aspects of laboratory QA/QC procedures.

- Method Blanks: For each batch of samples, method blanks should be run by the laboratory to determine the level of contamination associated with laboratory reagents and glassware. Results of the method blank analysis should be reported with the sample results.

- Laboratory Duplicates: For each batch of samples, one site should be used as a laboratory duplicate. For the laboratory duplicate analysis, one sample will be split into two portions and analyzed twice. The purpose of the laboratory duplicate analysis is to assess the reproducibility of the analysis methods. Results of the laboratory duplicate analysis should be reported with the sample results. Be aware that sample splitting methods such as churn and cone splitters may result in higher error for TSS duplicates.‘

- Matrix Spike and Spike Duplicates: Matrix spike and spike duplicates should be used to determine the accuracy and precision of the analysis methods in the sample matrix. Matrix spike and spike duplicate samples are prepared by adding a known amount of target compound to the sample. The spiked sample is analyzed to determine the percent recovery of the target compound in the sample matrix. Results of the spike and spike duplicate percent recovery are compared to determine the precision of the analysis. Results of the matrix spike and spike duplicate samples should be reported with the sample results.

- External Reference Standards: External reference standards are artificial standards prepared by an external agency. The concentrations of analytes in the standards are certified within a given range of concentrations. These are used as an external check on laboratory accuracy. One external reference standard appropriate to the sample matrix should be analyzed and reported at least quarterly by the laboratory. If possible, one reference standard should be analyzed with each batch of samples.

4.10 Conclusion

A successful and economically viable water quality sampling program requires careful forethought regarding the types of equipment for sample collection and types of constituents to be analyzed. To yield usable data, procedures for proper sample collection and analysis must be clearly defined upfront in a written monitoring plan and carefully followed in the field. A successful water quality monitoring program is also dependent on strong experimental design that will yield data sets enabling statistically significant conclusions to be drawn regarding BMP performance.

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Chapter 5
IMPLEMENTATION OF MONITORING PLAN

Proper implementation of a monitoring plan is as important as a well-designed plan. This chapter provides some general guidance on considerations and activities that can help implementation of a monitoring plan go more smoothly. Some factors considered are training of personnel, installation of equipment, and the mobilization and coordination with the laboratory.

5.1 Training of Personnel

Each member of the monitoring team must receive whatever training is necessary to properly perform his or her assigned roles. Generally, the first step is for each team member (including back-up personnel) to review the monitoring plan and health and safety plan. Next, the team members attend an initial orientation session that includes a "dry run" during which team members travel to their assigned stations and simulate monitoring, sample documentation, packaging, and so on. This all takes place under the supervision of the instructor (usually the principal author of the monitoring plan). Health and safety precautions should be reinforced during the dry run, along with QA/QC procedures. Periodic "refresher" orientation sessions should be conducted after long dry periods, or when the monitoring team composition changes. Typical components of a health and safety plan are provided in Exhibit 5-1. Exhibit 5-2 provides an initial list of resources that can be helpful in developing a health and safety plan (which is part of developing a monitoring plan that is discussed in Chapter 2), as well as educating those conducting sampling on key safety issues.

Exhibit 5-1. Representative Topics for Inclusion in a Health and Safety Plan
(Source: Caltrans 2000,
http://www.dot.ca.gov/hq/env/stormwater/special/guidance_manual/)

- 1.0 Introduction
- 2.0 Project And Safety Personnel
- 3.0 Site Information
- 4.0 Work Activities Covered By Health And Safety Plan
- 5.0 Hazard Assessment
  - 5.1 Chemical Hazards
  - 5.2 Confined Spaces
  - 5.3 Physical Hazards
  - 5.4 Biological Hazards
- 6.0 General Health And Safety Requirements
  - 6.1 Employee Clearance
  - 6.2 Site Safety Meetings
  - 6.3 Accident Reporting
  - 6.4 Prohibited On-Site Activities
  - 6.5 Communications
- 7.0 Site-Specific Health And Safety Requirements
  - 7.1 Special Medical Tests
  - 7.2 Special Training
  - 7.3 Physical Hazards
  - 7.4 Hazardous Materials Identification & Protection
  - 7.5 Confined Space Entry
  - 7.6 Traffic Control
  - 7.7 Personal Protective Equipment
  - 7.8 Site Illumination
  - 7.9 Biological Hazard
- 8.0 Emergency Response Procedures
  - 8.1 Hospital Information
  - 8.2 Emergency Route to Hospital
  - 8.3 First Aid & Related Equipment

Exhibit 5-2. Supplemental Health and Safety References

Centers for Disease Control and Prevention. http://www.cdc.gov/

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U.S. Geological Survey Memo WRD 99.01. *SAFETY-Traffic Control Plan for Field Operations from Bridges and along Roadways.* http://water.usgs.gov/admin/memo/policy/wrdpolicy99.01.html

U.S. Geological Survey Water Resources Division Immunization Program. http://water.usgs.gov/admin/memo/policy/wrdpolicy96.29.html

5.2 Installation of Equipment

If automated monitoring methods are used, then sampling and flow measurement equipment must be installed following manufacturer's instructions. Equipment installation procedures vary depending on the specific equipment and the configuration of the monitoring location. Some general recommendations for equipment installation are listed below:

- Personnel must follow the health and safety plan when installing equipment. Some monitoring locations may require use of protective clothing, traffic control, combustible gas meters, and special training in confined space entry procedures.

- Bubbler tubes, pressure transducers, and velocity sensors typically are mounted on the bottom of the channel in the middle of the channel cross-section, facing upstream. Ultrasonic depth sensors typically are mounted above the water surface.

- Automated sampler intake tubing should be mounted in a way that the tubing and intake do not interfere with the flow measurement device. Typically, the intake will be fitted with a strainer to prevent clogging.

- Probes, sensors, and intake lines usually are anchored to the pipe or channel. The intake tubing should be anchored throughout its length so that it will not bend, twist, or crimp under high flows. Often, it is advisable to route intake tubing through a conduit from the channel to the sampler housing to protect the tubes and lines from gnawing animals or from being crushed. For a well coordinated monitoring effort, it may be possible to install conduits in conjunction with construction of the Best Management Practice (BMP).

- Weirs and flumes must be secured to the bottom of the pipe or channel. If the monitoring location is in a swale, the weir or flume cutoff walls must be buried in each bank so that the structure extends all the way across the channel and all flow is directed through the weir or flume.

- If not installed inside a manhole vault, the flow meter and automated sampler should be placed in a sturdy shelter to protect the equipment from vandalism and other damage.

- If batteries are used as the power supply, fresh batteries should be installed at the frequency recommended by the manufacturer or before each anticipated storm monitoring event.

It is helpful to have a field equipment preparation checklist (see Exhibit 5-3 below) to ensure that appropriate equipment is available and in good condition. A field box should contain tools, spare parts, operation manuals for equipment, copies of the Monitoring Plan and Monitoring Checklist, safety equipment, and other supplies that might be useful during sample collection and transport. The field equipment box should be checked approximately 24 hours prior to the anticipated monitoring to ensure all equipment is included and in good condition.

Exhibit 5-3. Example Field Equipment Preparation Checklist

Documentation

Health and Safety Plan
Stormwater Monitoring Plan
Monitoring Plan checklists and field notebooks
Equipment manuals
Chain-of-custody forms/bottle labels/permanent markers/pen/pencils

Sampler

Graduated cylinder for sampler calibration
Spare suction line (0.24-in to 0.375-in diameter)
Spare strainer
Spare battery
Masonry anchors & screws
Masonry drill bits
Tubing anchors or galvanized steel strapping

Flowmeter

Depth-measuring rod
Data interrogator or laptop computer
Spare batteries
Area velocity sensor
Cable ties
Calibration equipment (see flowmeter manual)

Safety

Portable gas monitor (in one box only)
Safety line
Tripod, winch, and safety harness (1 per vehicle)
Flashing lights for vehicle
Traffic cones
Cell phone (or two way radios)
Flashlights (1 per person)
Gloves (protective leather and nitrile)
Hard hat (1 per person)
Goggles (1 set per person)

Miscellaneous

Battery powered drill
Hand tools (hammer, screwdriver, pliers, knife, hacksaw, wire strippers, measuring tape)
Manhole hook
Buckets
Ropes
Duct tape
Distilled water
Watch or stopwatch
Digital camera
Heavy duty hand truck
Cash and credit card

5.3 Testing and Calibrating Equipment

Water quality probes (e.g., pH, conductivity), automated samplers, and flow meters must be periodically calibrated in order to ensure reliable operation and credible results. Typical calibration procedures are summarized in this section; however, always follow the manufacturer's instructions when calibrating a specific monitoring device.

Calibration of pH meters, conductivity meters, dissolved oxygen meters, and other water quality instruments generally involves two steps:

1) Use the instrument to measure a known standard and determine how much the instrument's measurement differs from the standard.

2) Adjust the instrument according to the manufacturer's instructions until it provides an accurate measurement of the standard.

Automated sampling equipment should be calibrated after installation to ensure it pumps the correct volume of sample. The condition of the sampler pump and intake tubing, the vertical distance over which the sample must be lifted, and other factors can affect the volume drawn. Therefore, test the sampler after installation and adjust the sampler programming if necessary to be sure the system consistently draws the correct sample volume. For an extra level of assurance, installed equipment should also be calibrated prior to storm events, where feasible. It is important that the monitoring team understand the automated sample trigger conditions and the sampler program settings to ensure that the samples are being collected at the appropriate intervals along the hydrograph. A mock monitoring event, even for automated samplers, can be beneficial to ensure that sample collection is being triggered correctly.

Flow meters can be affected by the hydraulic environment in which they are placed; consequently, they should be calibrated after installation to ensure accuracy. Because sediments, debris, and other materials carried by stormwater can damage or clog bubbler tubes and pressure transducers used for depth measurements, they must be frequently inspected and calibrated by checking the flow depth with a yard stick or staff gage. Ultrasonic velocity sensors and other instruments that measure flow rate must also be inspected and checked against velocity measurements using a current meter.

5.4 Conducting Monitoring

After completing the preparations described above, manual or automated monitoring can be initiated for the storm events. Manual monitoring requires an increased level of staff effort to prepare for the storm. (Flow monitoring and water quality sample collection techniques are discussed in Chapters 3 and 4, respectively.)

The general steps for manual monitoring are:

1) The monitoring team leader or another designated person tracks the weather forecasts. For manual monitoring, a vigilant "weather watch” is critical in order to reach the site in time to monitor the initial runoff from a storm event and coordinate the monitoring team, pick-up ice, notify the laboratory, and so on. A close weather watch can also help avoid wasting time with "false starts" when a forecasted storm fails to materialize. Exhibit 5-4 provides a representative weather tracking protocol that can help this process go more smoothly.

2) When the weather forecasts indicate that a potentially acceptable storm is approaching, the monitoring team leader contacts the monitoring team and the analytical laboratory. If any of the primary team members are unavailable, the monitoring team leader arranges for back-ups. The team members check their instructions, communications protocols, monitoring equipment, and supplies to ensure they are ready.

3) The monitoring team leader contacts National Oceanic and Atmospheric Administration (NOAA), or some other meteorological service if better information is

available, to get updated forecasts as the storm approaches. When the forecasts indicate that the storm is likely to start within the next few hours, and it still appears likely to meet the storm selection criteria, the team leader directs the team members to proceed to their assigned monitoring stations so that they arrive before the predicted start time. The team leader also alerts the lab that samples are likely to be delivered soon.

4) The team members travel to their assigned locations and start collecting samples and taking flow measurements as soon as possible after stormwater runoff begins. The team completes the sample labels, chain-of-custody forms, and other field documentation.

5) During monitoring, team members in the field should be able to contact the team leader by cell phone to ask questions, notify him or her of changing conditions, receive direction, and so on. Additionally, for safety reasons, an expected return time and/or check-in time should be established (e.g., if the team has not returned or checked in within an expected timeframe, then someone needs to follow-up to ensure that the team is safe).

6) After the samples have been collected, ship or deliver the samples to the analytical laboratory, being sure to comply with temperature and holding time requirements specified in the sampling plan.

7) Normally, field personnel prepare all samples, including composting, filtering and preserving, prior to shipping to the laboratory.

8)

Exhibit 5-4. Example Standard Operating Procedure for Weather Tracking and Monitoring Preparation

The Storm Event Coordinator will review the daily National Weather Service forecasts (http://www.nws.noaa.gov) and track all potential rainfall events. If an event being tracked has a 75 percent or greater probability of generating 0.2 inches of rainfall within a 24 hour period, the Storm Event Coordinator will inform the Monitoring Team 72 hours before its predicted arrival and the Team will be placed in a "Prepare Mode".

Monitoring Team "Prepare Mode"

- Order bottles from lab and alert lab of possible monitoring activities (may want to keep a supply on hand during monitoring season)
- Assemble field equipment
- Arrange team members schedule for field activities
- Arrange vehicle for monitoring activities
- For first event of each season, check and flag all sample locations and assess site conditions, report any potential problems to Storm Event Coordinator

The Storm Event Coordinator will maintain frequent contact with the Weather Service and if the forecast still predicts a target magnitude event at 48 hours before its arrival, the Monitoring Team will be placed in a "Stand-By Mode".

Monitoring Team "Stand-By Mode"

- Identify Monitoring Team and arrange schedules for field activities
- Check bottle inventory against station check list
- Initiate chain of custody procedure
- Bench test and calibrate all field equipment
- Confirm team member schedules for field activities
- Arrange for vehicle to conduct monitoring activities

At 24 hours before the event is predicted to arrive if there is still a 75 percent probability that the storm will generate 0.2 inches of rainfall within 24 hours, the Storm Event Coordinator will receive Quantitative Precipitation Forecasts (QPF) every 6 hours (or more frequently) from the Weather Service and a monitoring "Alert" will be issued.

Monitoring Team "Alert Mode"

- Label bottles
- Check field boxes for supplies
- Ensure a sufficient amount of ice for sampling and sample transport
- Set up sampling equipment at sites (preferably during daylight hours)

(Continued on next page)

Exhibit 5-4 ***(continued).*** **Example Standard Operating Procedure for Weather Tracking and Monitoring Preparation**

At 12 hours before a target event is scheduled to arrive, a Go/No-Go decision on monitoring will be made by the Storm Event Coordinator. The latest QPF will be obtained from the Weather Service and sampler programming calculations will be done for each site; this information will be relayed to the Monitoring Team.

Monitoring Team "Go"

- Mobilize Monitoring Team
- Install fully charged batteries in samplers
- Program automated samplers
- Install clean bottles in samplers
- Check all tubing, connections, and strainer placement

Monitoring Team "No-Go"

- Retrieve sampling equipment
- Inventory, clean, organize, and prepare sampling equipment for next event

Once precipitation has begun, the Monitoring Team will go into "Sample Mode"

Monitoring Team "Sample Mode"

- Contact Storm Event Coordinator and confirm "Go" decision
- Place ice in automated samplers
- Follow site specific sampling plan or operating procedures

The general steps for automated monitoring are:

1) Perform routine inspection and maintenance to help ensure that the equipment will function properly when a storm event occurs.

2) Keep track of precipitation. After each storm, check the local rainfall records (or preferably a rain gage at or near the center of the basin) to see if the amount of precipitation and the antecedent dry period met your pre-determined criteria.

    - If the storm did not meet sampling plan criteria, remove the sample bottles from the sampler and replace them with clean bottles. Empty the sample bottles and arrange for them to be cleaned.

    - If the storm criteria were met, remove the sample bottles. Check them to be sure they collected the proper amount of sample. Check the sampling times against the storm duration to see how much of the storm was sampled (e.g., what portion of the hydrograph was captured). If sampling criteria were met, complete the sample labels, chain-of-custody forms, and other field documentation, then deliver the samples to the laboratory for analysis.

3) If the sampler overfilled or underfilled the sample bottles, refine the sampler programming.
4) Reset the sampler and inspect all of its systems for possible damage or clogging so that it will be ready to sample the next storm.

5.5 Coordinate Laboratory Analysis

Most stormwater monitoring programs involve laboratory analysis. Exceptions include: (1) field screening programs that rely solely on visual observations and field test kits; and (2) programs that rely on "in-situ" monitoring of indicator parameters (e.g., pH, dissolved oxygen, turbidity) using probes and data loggers.

It is a good idea to involve laboratory personnel in identifying the analytical methods and establishing communications protocols and QA/QC protocols. Typically, the laboratory will provide the pre-cleaned sample bottles and distilled/deionized water used for monitoring. Exhibit 5-5 provides guidance on proper bottle organization.

Exhibit 5-5. Bottle Organization Procedures

1) Bottles of proper size and material and sufficient quantity should be prepared by the analytical lab and delivered to the Monitoring Team at least 48 hours prior to the sampling event (see sample bottle order form). Bottles should be inventoried and checked against the site specific operating procedures for each monitoring station.
2) A separate 80-quart Rubbermaid Environmental Cooler should be prepared and clearly labeled for each set of samples at each monitoring station. The cooler should include the required bottles for sampling at that site as well as bottles for blanks and duplicates as required by QA/QC plan.
3) All sample bottles should be labeled prior to placement in sampler and as much information as possible should be filled out on the labels when bottles are dry. A second label or corresponding Sample ID No. should be place on sample bottle lid.
4) One set of clean beakers in Ziploc bags (1-250 ml and 1-500 ml) should be placed in coolers with bottles.
5) Powder-free nitrile gloves should be worn whenever handling clean bottles.

Sample Site Identification Information

Site Name	Site ID Number	Grab Sample Bottles	Automated Sample Bottles

Mobilization protocols should include notifying the laboratory when a storm monitoring event appears imminent. It is also good practice to contact the laboratory shortly after the monitoring event to ensure that the samples were received in good condition and to answer any questions the lab may have regarding the analyses to be conducted. Frequent communication with the laboratory helps reduce the risk of incorrect analysis and other potential unpleasant "surprises."

An essential aspect of strong coordination with the laboratory is proper completion of the chain-of-custody form provided by the laboratory. The chain-of-custody form is a legal document designed to track samples and persons who are responsible for them during preparation of the sample container, sample collection, sample delivery, and sample analysis. The chain-of-custody form must be filled out correctly and completely to minimize errors during the analytical process. Be sure to retain a copy of the completed chain-of-custody document and keep it accessible to answer questions that may arise from the laboratory.

General guidance for transporting, packing and transporting samples from the field to the laboratory include:

1) Clearly mark the analyses to be performed for each sample.
2) Fold the field-sampling sheets and chain-of-custody form and place them in plastic bags to protect the sheets during transport. Tape chain-of-custody form to the lid of the cooler.
3) Pack samples well to prevent breakage or leakage (samples should already be labeled) and provide additional protection for glass sample bottles (e.g., foam or bubble wrapping).
4) Sample should be packed in ice or an ice substitute to maintain a sample temperature of 4° C during shipping. Ice (or substitute) should be placed in double wrapped watertight bags to prevent leaking during shipping.
5) Using duct tape or packing tape, wrap the cooler twice to seal the opening.
6) On the sealing tape, write the date and time the sample container was sealed
7) Affix destination, identification, and FRAGILE labels to each shipping container.
8) Samples must be delivered to the analytical laboratory within maximum hold times. (For example, if bacteria samples are collected, delivery should be within 4 hours of sampling to ensure the 6-hour maximum holding time for bacteria is not exceeded.)

5.6 Conclusion

Effective implementation of the monitoring plan is a fundamental component of a successful BMP monitoring program. Careful attention to equipment installation and calibration, proper sampling techniques and handling, as well as strong coordination with the laboratory conducting the analysis is key to a properly implemented monitoring program. It is essential that the staff involved in implementation of the monitoring program be properly trained to conduct these tasks.

5.7 References

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Chapter 6
DATA MANAGEMENT, VALIDATION, AND REPORTING

Effective data management, validation and reporting are fundamental components of an effective stormwater Best Management Practice (BMP) monitoring study. This chapter provides basic recommendations for general data management, data validation, use of databases, data entry approaches to maximize efficiency and minimize errors, QA/QC techniques, reporting guidelines, and submission of studies to the BMP Database.

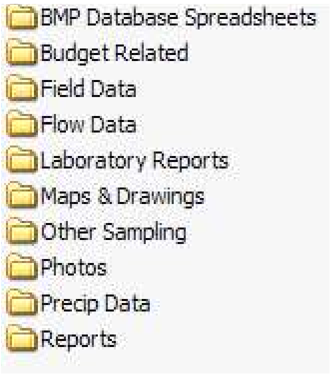
6.1 Recommendations for Data Management

A stormwater BMP monitoring program typically generates a considerable amount of information in a wide variety of forms. Before initiating monitoring, it is important to establish effective data management procedures to enable efficient storage, retrieval, and transfer of monitoring data. The Quality Assurance Project Plan (QAPP) should identify data management procedures, specifying measures such as:

- Central File: A central file to accommodate the hard copy information generated by the program and practical dating and filing procedures to help ensure that superseded information is not confused with current information.

- Field Forms: Well-designed and consistently used field forms promote standardized documentation and enable subsequent verification of field conditions. Field forms can be scanned on most modern copiers and stored electronically, along with other project data. Examples of field forms that can be customized to a particular study can be obtained from a variety of sources (e.g., http://ma.water.usgs.gov/fhwa/fhwaep.htm).

Exhibit 6-1. Example File Directory for BMP Monitoring



- Electronic Database: A database to accommodate electronic results of laboratory analyses, information recorded by data loggers (e.g., flow, precipitation, in-situ water quality measurements), maps in CAD or GIS, spreadsheets, and so on. An example electronic file structure is shown in Exhibit 6-1. As part of this system, it is important to clearly label draft and final reports, as well as validated and unvalidated data. Organizing digital photographs in subfolders according to date is also helpful.

- Contractor Instructions: Clear instructions to contractors regarding both raw data and processed data formats. It is not uncommon for expensive monitoring programs to lose valuable underlying data (e.g., flow data used to calculate event mean concentrations) when a contractor is no longer involved in a project.

- Computer Backup Guidelines: Instructions and requirements for frequency of backup of computer files. Although this may occur automatically in many office settings, simple manual backups onto CDs or DVDs will also work.

In most cases, the laboratory can provide the analytical results in an electronic format [i.e., an "Electronic Data Deliverable" (EDD)] that can be input directly into an internal water quality database, as well as the BMP Database. When preparing the chain of custody for the laboratory, request both PDF and open electronic formats (e.g., delimited text file, database or spreadsheet) of the data. Directly importing laboratory data increases efficiency and reduces data entry errors, as well as ensures a complete record of the results such as the correct name for the constituent analyzed, the test method, the detection limit and appropriate data qualifiers. In some cases, laboratories are also willing to output data to a custom format.

Data reports should be reviewed for completeness as soon as they are received from the laboratory. Reports should be checked against the sampling plan to ensure all requested analyses were performed and all required quality assurance (QA) data are reported for each sample batch. If problems with reporting or laboratory performance are encountered, corrective actions (i.e., re-submittal of data sheets or sample re-analysis) should be performed prior to final data reporting or data analysis.

6.2 Data Validation

Before uploading water quality data into a database or interpreting performance of BMPs, it is critical to evaluate the quality and adequacy of the laboratory analytical results. This evaluation is known as "data validation" or data quality review. The basic steps are listed below.

1) Check that all requested analyses were performed and reported, including QA/QC samples.

2) Check sample holding times to ensure that all samples were extracted and analyzed within the allowed sample holding times. (Typically, laboratories will provide an "H" qualifier when hold times are exceeded.)

3) Check that field QA/QC was acceptable. This includes a check of equipment blanks, field duplicates, and chain-of-custody procedures.

4) Check that the laboratory's performance objectives for accuracy and precision were achieved. This includes a check of method blanks, detection limits, laboratory duplicates, matrix spikes and matrix spike duplicates, laboratory control samples, and standard reference materials.

5) Check that surrogate recoveries were within laboratory control limits.

6) Assign data qualifiers as needed to alert potential users of any uncertainties that should be considered during data interpretation.

If the laboratory and field performance objectives were achieved, further data validation is generally not needed. Specifics of the instrument calibration, mass spectral information, and run logs are not usually recommended for review unless there is a suspected problem or unusual circumstances regarding decisions that will be made based on the data. If performance objectives were not achieved (e.g., due to contaminated blanks, matrix interference, or other specific problems in laboratory performance), the resulting data should be qualified. U.S. Environmental Protection Agency (EPA) functional guidelines for data validation should be used as a guide for qualifying data (see EPA 2004). Data qualifiers used in the BMP Database are consistent with the EPA's Water Quality Exchange (WQX) format (http://www.epa.gov/storet/wqx.html).

6.3 Using or Establishing Databases

Databases can be an efficient approach to storing monitoring data in a standardized format that facilitates data analysis. The International Stormwater BMP Database uses a combination of data entry spreadsheets in Microsoft Excel and a master database in Microsoft Access (WWE and Geosyntec 2009). Both the spreadsheets and the master database can be downloaded from http://www.bmpdatabase.org. One of the benefits of the BMP Database is that it identifies the types of data that need to be reported to conduct performance analysis for various BMP types. For various data elements, dropdown lists are provided that follow standardized rules so that future searches (queries) of the database can be conducted on specific parameters. For example, all copper data use identical nomenclature, so a query for copper retrieves all of the copper data. The BMP Database also provides ample space for providing narrative comments.

One of the benefits of relational databases, which include multiple tables linked together on key fields, is that large amounts of data can be stored in a more efficient manner. In the BMP Database for example, the user defines storm or base flow events that are monitoring based on start date and assigning a storm number. Once the storm event has been assigned an identifier (Storm Event #1), then that identifier can be used to link a table of storm event data to a table of flow data to a table of water quality data associated with the event. This approach is particularly valuable when there are "one to many" relationships such as one precipitation event with many water quality constituents monitored. In such relational database structures, it is important to ensure that the identifiers linking each table to event data are accurately assigned (e.g., are the precipitation, flow and water quality data properly linked to each other for Storm #1?).

6.4 Data Entry Approaches

Errors in data entry can cause significant problems in performance analysis and can waste time later if data entry is not carefully checked up front. The following techniques are helpful in reducing data entry errors:

- Require use of electronic data deliverables from laboratories. Hand entry of laboratory data increases the likelihood of errors and is unnecessarily time-consuming. A common problem to look for in electronic data deliverables is sample location nomenclature errors related to handwriting interpretation by lab technicians. For example, site location MW-1 could easily be confused with MW-7. These types of errors need to be corrected at the time of data upload, rather than at the time of data analysis.

- When entering field data (e.g., pH, temperature, conductivity), it is helpful to have one person enter the data and another back-check the data to field notes.
- In cases where large backlogs of data must be entered by hand, double data entry can be a tool to minimize errors in a time-efficient manner.

Although data entry is the most straightforward aspect of most monitoring programs, it is also an area that requires significant attention to detail so that conclusions drawn from subsequent performance analysis are accurate.

6.5 QA/QC Techniques

Depending on the complexity of the project, a wide range of QA/QC techniques can be implemented. This section focuses on basic outlier screening and preliminary evaluation techniques that are applicable to most monitoring projects.

6.5.1 Outlier Screening/Analysis

Before conducting performance analysis, the water quality, flow, precipitation and other data should be screened for outliers. This screening helps to identify errors in data entry, as well as unusual values reported for an event. Although several specific techniques can be conducted as described below, this is a good time to have an experienced engineer or scientist give the data a “reality check.” Outlier screening should include these tasks:

- <u>Precipitation Data</u>: Given that most BMP monitoring programs monitor a limited number of storms, review of precipitation data for outliers is relatively straightforward. If excessively large rainfall events are measured, then a nearby rain gage can be used to cross-check the data set. In cases where the hyetograph for the precipitation event is questionable, consider site factors such as clogging due to bird waste or the influence of spring snow storms then qualify, adjust, or invalidate the data as appropriate. On sites with multiple rain gages, significant variation between gages should be a flag to double-check the data to ensure that the reported differences were real.
- <u>Flow Data</u>: Flow measurement is the portion of stormwater BMP monitoring that is most likely to include errors. Checks on flow data can include rough calculations that combine precipitation with tributary area (e.g., simple Rational Method calculations) and compare the results to the monitored flow, asking common sense questions such as “Is the amount of runoff physically possible, given the amount of rainfall that occurred?” Other checks could include comparing flow data for similar rainfall

events to assess whether the data appear to be reasonably comparable. In some cases, where systematic flow measurement errors are discovered, an adjustment factor can be applied to the flow measurements, provided that the adjusted values are identified as adjusted or estimated. Additionally, it is important to compare inflows to outflows. If outflows are significantly greater than inflows, then the flow data should be carefully checked. In some cases, real contributions from groundwater or sheet flow not captured at the inflow monitoring location need to be taken into consideration and included in study reports. Rather than discarding the inflow data, it may be better to provide a modeled estimate of other flow contributions and include this information when reporting data. This is particularly important in the context of Low Impact Development (LID) monitoring where proper evaluations of volume reduction are study objectives.

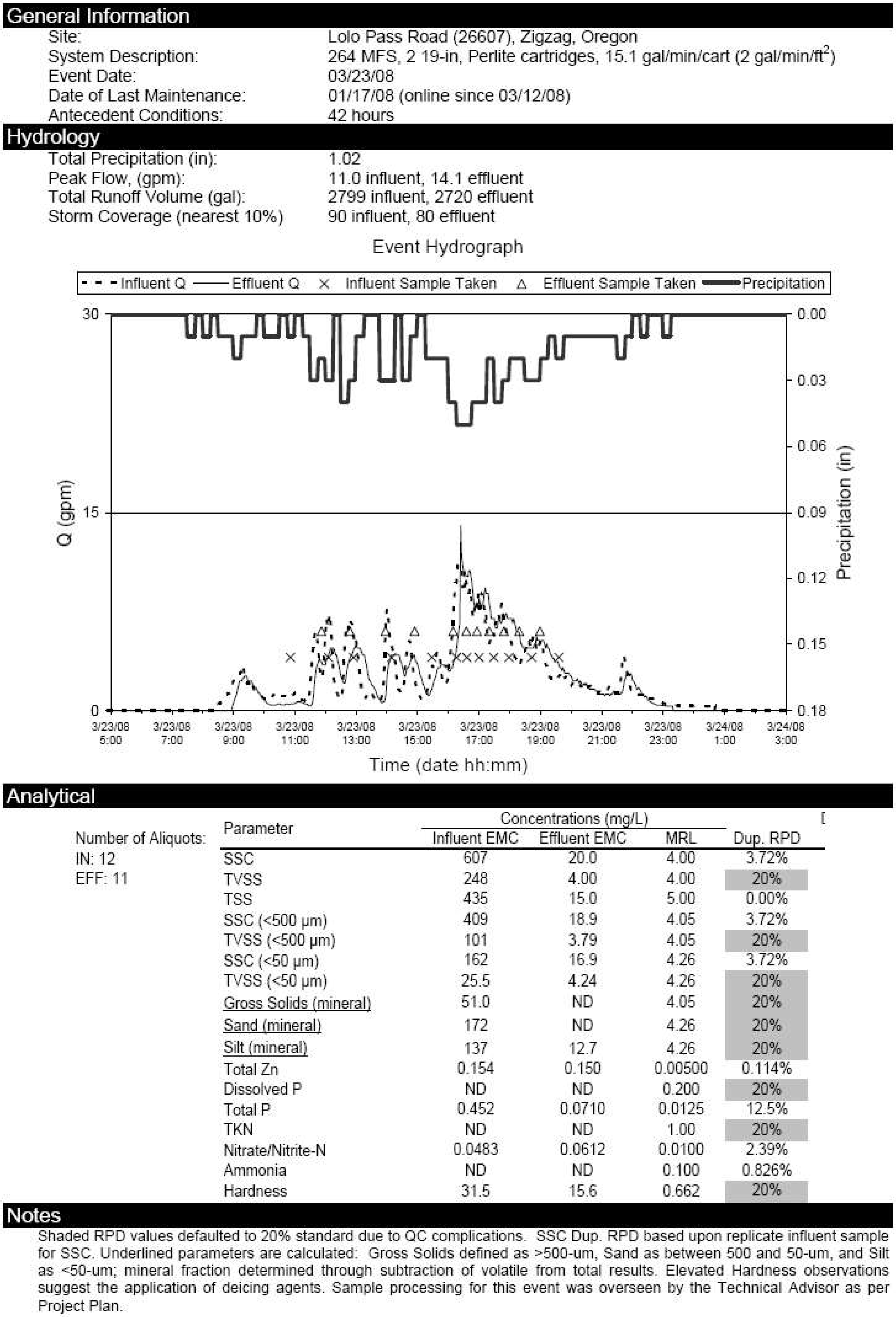
- Water Quality Data: For hand-entered data, outlier screening for data entry errors can often be found by using simple spreadsheet functions to identify maximum and minimum values. Common errors such as misplaced decimal points can easily be identified for parameters such as pH and temperature using this technique. For other parameters, standard deviations can be calculated to identify results greater than three standard deviations above the mean as a screening tool to flag results that may need to be double-checked. There are no simple approaches for outlier screening for some constituents such as bacteria data, which can vary orders of magnitude between storms. Simple screening should also include checking units reported for each constituent to ensure that simple errors such as reporting mg/L instead of µg/L for metals have not occurred and to be sure that units have been provided for all constituents. Additionally, water quality data screening should include a check of reported results and qualifiers against method detection limits to ensure that appropriate qualifiers have been provided. For example, non-detects should have a "U" qualifier.

Overarching all of these considerations is the simple fact that those interpreting the data need to have direct familiarity with the site. Many errors in BMP reporting can be avoided by taking into consideration common sense understanding of the conditions present at the site.

6.5.2 Preliminary Data Evaluation

After the chemical data have been validated, a preliminary data evaluation should be conducted to determine whether enough data of sufficient quality have been collected to meet the study goals. Using the validated analytical results, graphically plot flow and rainfall data versus time for each storm event in order to produce a storm hydrograph (flow rate versus storm duration). It is often helpful to plot rainfall volume versus storm duration on the same graph and mark the times when the grab or composite samples were collected. See Exhibit 6-2 for an example individual storm report. This information can be very helpful in interpreting the chemical results and, if conducted after the first few storms, can be useful tool in identifying systematic errors in the monitoring (e.g., pacing of sample collection). Individual storm reports can also be included in appendices of the monitoring report to ensure that key information about the monitoring site and event are well documented and that information is not lost over time.

Exhibit 6-2. Example Individual Storm Report (Source: Lenhart 2009)



General Information

Site:	Lolo Pass Road (26607), Zigzag, Oregon
System Description:	264 MFS, 2 19-in, Perlite cartridges, 15.1 gal/min/cart (2 gal/min/ft^2)
Event Date:	03/23/08
Date of Last Maintenance:	01/17/08 (online since 03/12/08)
Antecedent Conditions:	42 hours

Hydrology

Total Precipitation (in):	1.02
Peak Flow, (gpm):	11.0 influent, 14.1 effluent
Total Runoff Volume (gal):	2799 influent, 2720 effluent
Storm Coverage (nearest 10%)	90 influent, 80 effluent

Event Hydrograph

Analytical

Number of Aliquots:
IN: 12
EFF: 11

Parameter	Concentrations (mg/L)			
	Influent EMC	Effluent EMC	MRL	Dup. RPD
SSC	607	20.0	4.00	3.72%
TVSS	248	4.00	4.00	20%
TSS	435	15.0	5.00	0.00%
SSC (<500 µm)	409	18.9	4.05	3.72%
TVSS (<500 µm)	101	3.79	4.05	20%
SSC (<50 µm)	162	16.9	4.26	3.72%
TVSS (<50 µm)	25.5	4.24	4.26	20%
Gross Solids (mineral)	51.0	ND	4.05	20%
Sand (mineral)	172	ND	4.26	20%
Silt (mineral)	137	12.7	4.26	20%
Total Zn	0.154	0.150	0.00500	0.114%
Dissolved P	ND	ND	0.200	20%
Total P	0.452	0.0710	0.0125	12.5%
TKN	ND	ND	1.00	20%
Nitrate/Nitrite-N	0.0483	0.0612	0.0100	2.39%
Ammonia	ND	ND	0.100	0.826%
Hardness	31.5	15.6	0.662	20%

Notes

Shaded RPD values defaulted to 20% standard due to QC complications. SSC Dup. RPD based upon replicate influent sample for SSC. Underlined parameters are calculated: Gross Solids defined as >500-um, Sand as between 500 and 50-um, and Silt as <50-um; mineral fraction determined through subtraction of volatile from total results. Elevated Hardness observations suggest the application of deicing agents. Sample processing for this event was overseen by the Technical Advisor as per Project Plan.

Generally, stormwater quality variability is so high that statistical evaluation is not worthwhile until several events (at least four) have been monitored. Once results for several events are available, basic summary statistics should be calculated that indicate how well sample results represent stormwater quality at a given site. Summary statistics include sample mean; variance; standard deviation; coefficient of variation; coefficient of skewness; median; and kurtosis. Because stormwater quality typically exhibits a lognormal distribution (EPA 1983), calculate these descriptive statistics based on an assumed lognormal distribution unless other information suggests an alternative distribution is more appropriate. Use the initial statistical analysis to determine whether it will be useful to statistically test various hypotheses regarding the existing data set. For example, if the standard deviations are several times larger than the means (i.e., the coefficient of variation is 3 or more), hypothesis testing may not be worthwhile. It may be necessary to conduct additional monitoring to compensate for the observed variability and allow statistically significant differences to be discerned. If initial statistical analysis indicates that the samples are representative of water quality at the site, then move forward with more definitive evaluations using the techniques described in Chapter 7.

6.6 Reporting Results

Most monitoring programs involve two types of reports: status (or progress) reports and final reports. To determine the appropriate frequency of status reports, consider the monitoring frequency and objectives, particularly any permit requirements. Many programs produce status reports on a quarterly or semi-annual basis. A typical status report may contain the following information:

- Summary of work accomplished during the reporting period, including an assessment of how the work completed compared to project objectives and goals (e.g., number of qualified storms collected versus number of storms targeted).
- Summary of findings.
- Summary of contacts with representatives of the local community, public interest groups, or state federal agencies.
- Changes in key project personnel, equipment or monitoring approach.
- Projected work for the next reporting period.

Prepare more comprehensive reports at the end of the monitoring program (for short-term programs) or at the end of each year (for multi-year programs). Consider including the above-listed information and the following information in the annual or final report:

- Executive summary.
- Monitoring program background and objectives.

- Tributary watershed characteristics and land use conditions.
- Adequate BMP design description (e.g., key parameters, photos, sketch plan).
- Monitoring station descriptions, analytical parameters, analytical methods, and method reporting limits.
- Summary descriptions of the site conditions and monitoring locations, equipment inspections and calibrations, and so on.
- Sample collection, precipitation, and flow measurement methods.
- Flow, precipitation, and water quality results and data validation information.
- Unusual or unexpected site conditions affecting use of the data.
- Qualitative and statistical data evaluations/hypothesis testing as required for the specific program objectives.
- Summary and conclusions, including any caveats or qualifying statements that will help the reader understand and use the reported information in the appropriate context.
- Recommendations regarding management actions (e.g., changes in monitoring program).
- Appendices with individual storm reports, laboratory data, and so on. Data CDs can be included with printed reports as an appendix.

6.7 Submitting Data to the International Stormwater BMP Database

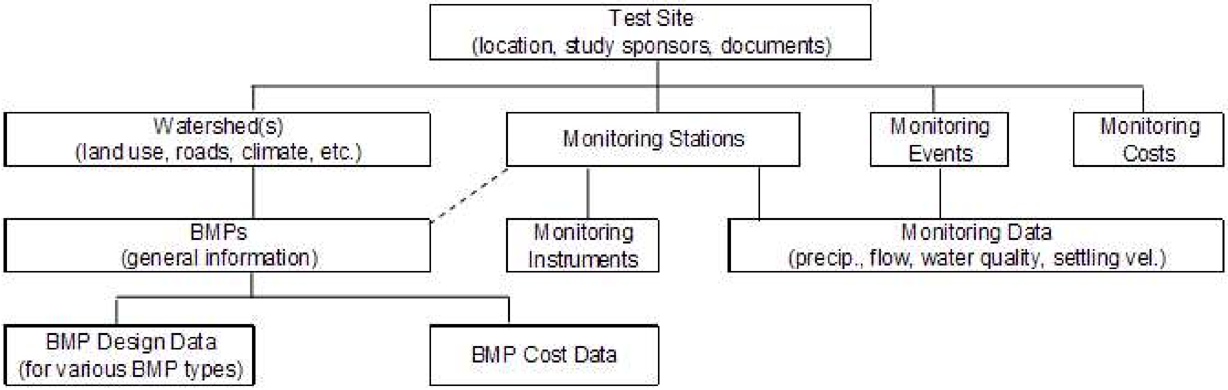
To submit data to the BMP Database, data must be entered into the most current version of the Microsoft Excel spreadsheet package available for free download from the BMP Database website (http://www.bmpdatabase.org/DataEntry.htm). Appendix A provides a hard copy of forms identifying the data requested for each study and/or BMP type as of 2008. A description of the key data requested is briefly described throughout the remainder of this section.

In order for a study to be accepted for inclusion in the database, all field designated as "required" fields must be provided. Depending on file size, the spreadsheet package can be "zipped" and emailed to the current BMP database contact identified on the project website, or a CD containing the data can be submitted. The submitted study is then reviewed for completeness and a series of reasonableness checks for the data (comparable to those described in Section 6.5) are completed prior to acceptance in the database. In most cases, minor follow-up is required to clarify issues related to the data submittal. Once the study is accepted in the database, it will be posted to the BMP Database website for public access. Provided that the study meets the performance analysis criteria for the database, statistical analyses will be conducted and made available to the public. In some cases, studies accepted into the database are not included in statistical analysis due to unique study designs that are not suitable for large-scale data set analysis.

6.7.1 Overview of Data Requirements for the BMP Database

Exhibit 6-3 contains a summary of the types of data requested by the BMP Database followed by descriptions of each data category.

Exhibit 6-3.
Conceptual Overview of Data Requirements for Submittal to the BMP Database



6.7.2 General Test Site Information

The purpose of the general test site data set is to identify the study, the study location, all involved parties, and the cost of monitoring for the study. Additionally, the study document spreadsheet enables the user to attach supporting information such as links to published studies, quality assurance plans, photos, BMP and site layouts, and other information. Climate information is also entered at the test site level based on an EPA-sponsored report by Driscoll et al. (1990) *Analysis of Storm Event Characteristics for Selected Rainfall Gages throughout the United States*. Only one test site can be entered in each spreadsheet package.

6.7.3 Monitored Events

The purpose of the monitoring event table is to develop a user-defined list of events monitored at the test site so that precipitation, flow, and water quality data can easily be paired together. Events are defined at the test site level since most monitoring designs will monitor the same events at reference watersheds, and multiple BMPs may be monitored for the same events. Additionally, LID studies may be monitored for the test site as a whole rather than at each individual BMP or integrated management practice (IMP) at the study site. For example, rather than monitoring 50 individual rain gardens, an assessment of runoff for the overall development may occur at the downstream portion of the site.

6.7.4 Watershed Information

The purpose of the watershed table is to identify the conditions in the area tributary to the BMP. For example, important factors for successful designs of infiltration-type BMPs include watershed parameters such as soil type, imperviousness, and storm drainage system efficiency. Since initial release of the BMP Database, the Federal Highway Administration and various state departments of transportation have taken interest in the database. As a result, additional information is now being requested for sites located along highways.

More than one watershed may be present at a BMP test site for studies that use a reference (i.e., control) watershed to compare BMP performance. This approach is often the case for non-structural BMP and LID studies. For LID studies, there may be more than one reference watershed in cases where pre-development hydrology and water quality for the site is monitored, as well as a comparative watershed developed using traditional development designs. In order to conduct valid comparisons of performance between test watersheds and reference watersheds, it is critical to thoroughly document the watershed conditions for both. For example, a test and reference watershed could have the same tributary area and number of homes (e.g., “look the same”), but the underlying soil types could be dramatically different, which would be a critical difference between the two watersheds in terms of evaluating performance of the LID design.

6.7.5 General BMP Information

General information and cost data for BMPs are requested for all BMP types, including structural and non-structural BMPs and LID sites. General information requested includes parameters such as date of installation, various design parameters, maintenance and rehabilitation types and frequencies, and cost data. An overview of the type of information requested for structural, non-structural, and LID sites is provided below.

Structural BMPs

Data requested for each structural BMP vary according to the following common groups of BMPs: Detention (Dry) Basins, Manufactured Devices, Retention (Wet) Ponds, Infiltration Basins, Percolation Trenches/Dry Wells, Porous Pavement, Wetland Basins, Wetland Channels/Swales, Grass Filter Strips, Media Filters, Bioretention, Stormwater Harvesting (cisterns), and Green Roofs. An “Other” BMP category is also provided to enable flexibility for entry of BMPs that may not fit a pre-defined category. A “Treatment Train” BMP option is also provided. Most of the parameters requested in the structural BMP tables are required in order to compare the effectiveness of various BMP designs. Exhibit 6-4 provides an example of design data requested for a bioretention BMP.

In order for monitoring data to be interpreted in proper context, it is important to provide thorough documentation of the BMP as constructed in the field, identify whether engineering oversight was provided during construction, and provide a proper description of the BMP’s condition during the study. For example, a common problem with bioretention cells and pervious pavements is that the as-built condition deviates from the design (Personal Communication with Bill Hunt, North Carolina State University). Without such information, poor performance of a BMP may be falsely attributed to design characteristics, when the design conditions did not actually exist in the field. Additionally, a well designed and properly installed, but poorly maintained BMP, is unlikely to perform well. It is important to clearly document the maintenance and/or rehabilitation status of the BMP so that researchers using data from the study can appropriately group BMPs with comparable maintenance conditions for performance analysis. The BMP Database accepts properly conducted studies, regardless of whether the BMP performs well, because one of the primary long-term purposes of the BMP Database is to identify factors affecting BMP performance. Improper installation and poor maintenance are key factors that must be properly documented.

Non-Structural BMPs

Non-structural BMP data requested are generally narrative/descriptive information on the type and extent of BMP practice being implemented, as well as cost data. For the purposes of the BMP Database, non-structural BMPs have been divided into the general categories of education, maintenance, recycling, and source controls. LID strategies often incorporate a variety of site planning and development approaches that include non-structural measures such as conservation of natural areas, preservation of soils with high infiltration capacities, minimizing disturbance, preservation of natural drainage paths, and so on. These types of non-structural LID practices would be entered into the database under the Site-level LID BMP type, as opposed to the traditional non-structural BMP category.

Evaluating non-structural BMP characteristics is new ground for many. Defining measurable (i.e., quantifiable) parameters for non-structural BMPs is an evolving science. When more than one non-structural BMP is employed, it can be extremely difficult, if not impossible, to isolate the effectiveness of one BMP from the effects of other non-structural BMP(s) being tested at the same site. Also, a significant amount of data is needed to discern differences in water quality results between comparable watersheds with and without non-structural BMPs. For this reason, non-structural BMP testing programs will typically need to take place over more than one year. It is likely that confounding variables will be difficult to identify and to isolate in non-structural BMP tests.

LID Sites

Because LID sites attempt to mimic pre-development site hydrologic conditions by controlling runoff close to its source, BMPs (or Integrated Management Practices) are typically dispersed throughout a development site. Reporting for LID sites includes both individual practices and performance for the overall site. In cases where individual LID practices (e.g., bioretention cells) are monitored, reporting protocols the individual practices described under “structural BMPs” would be used, whereas when site-scale LID monitoring is conducted, a set of parameters describing the extent to which a broad suite of LID practices is implemented would be used. These reporting parameters would be provided in addition to previously described watershed and monitoring data provided for conventional studies. Exhibit 6-5 contains initial recommendations for reporting for site-scale LID studies. These recommendations are focused on describing the extent to which LID has been implemented at a site. Chapter 8 provides additional information on study design for LID sites and other metrics that can be used to evaluate and compare performance of LID sites.

Exhibit 6-4. Example of BMP Design Information Requested for Bioretention

Part 1. General BMP Design Information
BMP Name
Type of BMP Being Tested
Basis of Design (e.g., 2-yr, 24 hr storm, design treatment flow rate)
Purpose of BMP (treatment objectives)
Source of Design Guidance for BMP
Date Facility Placed in Service
Number of Inflow Points
BMP Designed to Bypass or Overflow
Upstream Treatment Provided? (Y/N)
Describe Upstream Treatment (if any)
Name of Upstream BMP(s) (list sequence)
General Configuration of BMP in Tributary Watershed (i.e., end of pipe, source control, off-line)
Was qualified engineering oversight provided at construction?
Was structure installed as designed?
General Description of Site Activities/Conditions Influencing Pollutant Loading to BMP
Maintenance Type and Frequency
Last Rehabilitation Date
Type of Rehabilitation
Description, Types, and Designs of Outlets
Qualitative Evaluation of BMP Condition (vegetation, soils, odors, etc.)
For BMPs without permanent pool, does surface ponding exist beyond design drain time? (Y/N)
If clogging present, estimate % of total surface area of structure affected
Describe BMP/Comments

Part 2. Bioretention Design Information
Type of Bioretention (pick from drop-down list)
Ratio of Tributary Area to Bioretention Surface Area
Is Pretreatment Provided? (Y/N)
Description of Pretreatment, if present
Description of Flow Entrance
Bioretention Surface Area
Average Ponding Depth above Bioretention Media Surface
Ponding Volume above Bioretention Media Surface
General Shape of Bioretention Feature (triangle, oval, rectangle, etc.)
Is "Internal Water Storage Zone" Created? (via underdrain placement above bottom of media)
Subsurface Storage Volume
If subsurface storage provided, then height of outlet above bottom of bioretention media
Bioretention Media: Natural or Amended
Bioretention Media Depth
Bioretention Media Design Specifications
Bioretention Media "P" Index (Phosphorus)
Description of Supplemental Bioretention Media Characteristics
Description of Vegetation Community
Description of Mulch (if present)
Surface Infiltration Rate (at time of study)
Design Infiltration Rate (including safety factor for clogging)
Number, Description and Dimensions of Underdrain(s), if present
Underdrain Gravel Layer Thickness, if present
Description/Dimensions of Surface Overflow
Is a Hydraulic Restriction Layer (Liner) Provided?
Description of Hydraulic Restriction Layer, if present
Seasonal High Water Table Position Relative to Invert
Comments

Exhibit 6-5. Low Impact Development at Site Level (Horner 2009)

Data Element	Brief Description
BMP Name (Overall LID Site Name)	User-defined site name relates back to "General BMP" data entry spreadsheet.
Describe Site Design (include key elements of design)	Provide "big picture" of site design objectives and key design elements.
Describe Monitoring Design (to ensure proper use of data)	Describe monitoring design relationship to design elements.
Instructions for Describing Site Features: Quantitative data should be provided to the extent it is available. If the practice is not implemented, this should be stated instead of leaving the field blank. For discrete practices (e.g., permeable pavement, bioretention), design data should also be provided in their respective BMP tables.	
Conservation Features	Includes preservation of existing trees, other vegetation, and soils.
Minimizing Disturbance	Includes minimizing soil excavation and compaction and vegetation disturbance.
Minimizing Building Coverage	Includes minimizing impervious rooftops and building footprints.
Minimizing Travelway Coverage	Includes constructing streets, driveways, sidewalks, and parking lot aisles to the minimum widths necessary, provided that public safety and a walkable environment for pedestrians are not compromised.
Maintaining Natural Drainage Patterns and Designing Drainage Paths to Increase Time of Concentration	Includes measures such as maintaining depressions and natural swales; emphasizing sheet flow instead of concentrated flow; increasing the number and lengths of flow paths; maximizing non-hardened drainage conveyances; and maximizing vegetation in areas that generate and convey runoff.
Source Controls	Includes measures such as minimizing pollutants; isolating pollutants from contact with rainfall or runoff by segregating, covering, containing, and/or enclosing pollutant-generating materials, wastes, and activities; conserving water to reduce non-stormwater discharges.
Permeable Pavements	Includes constructing low-traffic areas with permeable surfaces such as porous asphalt, open-graded Portland cement concrete, coarse granular materials, concrete or plastic unit pavers, and plastic grid systems. Representative applications may include driveways, patio slabs, walkways and sidewalks, trails, alleys, and overflow or otherwise lightly-used parking lots.
Natural Drainage System Elements	Includes bioretention areas (rain gardens), vegetated swales, vegetated filter strips, and other similar features.
Stormwater Harvesting	Includes use of cisterns, rain barrels, or rain storage units.
Green Roof (vegetated)	Includes vegetated roofs with stormwater-related design components.
Other Site Features	Enables user to define other key site features or traditional BMPs.
Additional Facilities for Flood Control	Used to assess extent to which LID is used for water quality and flood control, or water quality only. Some LID sites have "hybrid" characteristics incorporating LID practices with traditional flood control approaches (e.g., are centralized detention and LID techniques).
List BMPs Monitored Within LID Site	Relates overall LID site design to individual practices monitored and/or implemented at the site (e.g., bioretention, permeable pavement).
Comments/Other Description	Describe other unique aspects of the site design or general comments.

6.7.6 Monitoring Stations

Monitoring stations must be identified for the test site as a whole, and then the relationship of each monitoring station to each BMP at the test site must be identified as monitoring inflow, outflow, subsurface conditions, sediment/solids, or some type of intermediate location within the BMP. For test sites that contain more than one BMP, two BMPs may share the same monitoring station; the station monitors the effluent from one BMP which is also the influent to a downstream BMP. In such cases, the relationship of the monitoring station must be identified relative to each BMP. A unique monitoring station name must be assigned to each monitoring station at a test site. At LID sites, it is not uncommon to have distributed controls throughout the watershed in combination with a larger flood control structure at the downstream end of the development. A clear understanding of the relationship of multiple monitoring stations to the site design is important for all BMPs, but is particularly important for proper interpretation of data from LID sites.

Information on instruments installed at monitoring stations is also important. Multiple instruments may be present at a single monitoring station. This information provides much insight into the flow gaging and sampling techniques used and the reliability of the data collected at the site. As a result, instrumentation reporting should be encouraged for all new evaluation efforts.

6.7.7 Monitoring Results

Monitoring results may include precipitation, storm runoff or base flow, water quality data, particle size distribution and/or settling velocity distributions associated with a monitoring event. Monitoring results must be reported in association with previously defined monitoring events and monitoring stations. For sites also monitoring groundwater levels, the water quality spreadsheet can be used to enter depth to groundwater. Each data set is briefly described below.

Precipitation

Precipitation data such as date and time that the event began and ended, total depth and peak one-hour precipitation rate are useful parameters for evaluating BMP performance. For example, a BMP may perform well for a low-intensity, short duration storm, but perform poorly for storms of longer duration. This type of information can help to explain variations in BMP performance.

Flow (Runoff and Base Flow)

Storm runoff directly affects the hydraulics of BMPs. Base flow data are also useful to understand the type of pollutant loading that occurs under dry weather conditions. Types of runoff data requested include runoff volumes into, from, or bypassing the BMP, and peak flow rates. Base flow data requested include flow rates. The BMP Database requests summary flow data, as opposed to continuous flow records; however, researchers may also submit raw data separately for archiving with the BMP Database. Although continuous flow data are valuable to researchers, management of continuous flow data for numerous studies is beyond the current scope of the BMP Database.

For LID sites and techniques, estimates of infiltration and/or groundwater measurements are valuable for evaluating performance of the site. These measurements can be entered into the Water Quality table, which follows EPA's WQX protocols for a variety of measurements in addition to water quality. (See the pick-list in the BMP Database spreadsheets for appropriate reporting parameters.)

Water Quality

Water quality data in combination with flow data for a monitoring event are used to calculate loads of each constituent, which are fundamental for comparing the performance of BMPs at different sites, locations, and regions. The BMP Database spreadsheets are designed to be compatible with many EDD formats now offered by laboratories and are generally based on EPA's WQX format, using "Modern" STORET terminology. The spreadsheet data entry approach enables pasting of EDDs into the database, thereby reducing the likelihood of data entry errors.

Particle size distribution data, which are important to evaluating the performance of many BMP types (particularly manufactured devices), can be entered into the water quality data table using WQX codes provided in a pick-list. As previously noted, a variety of hydrologic parameters such as soil moisture measurements and water quality samples from lysimeters and groundwater depths can also be entered into the Water Quality table as well. (Also see Chapter 4 for a discussion of suspended sediment sample collection and analysis issues.)

6.8 Conclusion

Proper data management, validation, and reporting are essential for a successful monitoring program. Many of these tasks are based on common sense, but are often overlooked in stormwater BMP monitoring. A well validated and documented data set is a fundamental building block for sound data evaluation and long-term value of the monitoring program. The BMP Database is a tool that can be used to ensure that key characteristics of stormwater BMP studies are systematically reported in a manner that enables comparisons of BMP performance locally and nationally.

6.9 References

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Chapter 7
BMP PERFORMANCE ANALYSIS

The analysis of Best Management Practices (BMPs) performance data is often complex and challenging. While the data collection and analysis methods used must suit the objectives of the study, consistency is needed to efficiently facilitate the use of individual study results as well as make broader conclusions with regard to the performance of larger classes of BMPs. Stormwater BMPs have been increasingly implemented over the last few decades to control stormwater runoff and potential pollutant discharge. Recently, Low Impact Development (LID) techniques have become a popular type of stormwater BMP to reduce runoff volumes and associated pollutant loads at or near the source. However, unlike traditional BMPs such as extended detention basins, LID techniques are distributed over a wide area and often do not have a clearly defined inlet and/or outlet. This presents numerous challenges not only for data collection, as discussed previously, but also for data analysis as discussed here.

7.1 Concentrations, Loads, and Volume Reductions

A variety of metrics or measures are available for assessing and quantifying the amount of pollutant conveyed to and from a BMP. Three primary measures are commonly used: concentration of stormwater at an instantaneous point in time (grab samples); the total contaminant load conveyed over a specified duration (e.g., individual storm, daily, weekly); or the event mean concentration (EMC).

7.1.1 Concentrations

Concentrations measured at individual points in time can be useful for BMP efficiency evaluations. Concentrations resulting from samples collected at specific times during an event allow for the generation of a pollutograph. A pollutograph is a plot of the concentration of pollutants as a function of time. Generating pollutographs facilitates the analysis of intra-event temporal variations in runoff concentration. For example, pollutographs can be used to determine if the “first-flush” phenomenon was observed for a specific event. Detailed concentration data is one of the approaches for assessing concentrations of pollutants that have acutely toxic effects, particularly where runoff from storm events constitutes a significant proportion of downstream flow. Under some circumstances, reduction of peak effluent concentrations may be more important than EMC reduction.

The cost of implementing a monitoring program that collects sufficient data to evaluate the temporal variation in runoff and BMP effluent concentration can be high. The trade-off between collecting data from a larger number of events as opposed to collecting detailed concentration data from intra-storm periods often limits the utility of studies that collect detailed concentration data. This type of detailed monitoring is best when focusing on outflow monitoring rather than inflow and outflow.

7.1.2 Contaminant Loads

Contaminant loads are typically calculated by using an average concentration multiplied by the total volume of flow over the averaging period. A variety of methods are available for estimating both the average concentration and the total flow volume. The method chosen depends on the sampling and flow measurement techniques used at the site. Average concentrations may be estimated by collecting time weighted samples, flow weighted samples, or a combination of the two. Likewise, flow data can be collected continuously, intermittently, or modeled from other hydrologic information, such as rain gage information or flow-monitoring conducted in a nearby watershed that has been correlated to the flow at the water quality sampling location. Many BMP monitoring studies focus efforts on water quality sample collection and neglect flow measurement. Accurate flow measurement or well-calibrated flow modeling is essential for load estimation.

Contaminant loads are often most useful when assessing the impact to receiving waters, such as lakes or estuaries, where long-term loadings can cause water quality problems outside of discrete storm events. When the effluent flow rate from a particular BMP is small compared to the flow rate of the receiving water body, potential downstream impairments depend on the absolute load of pollutant rather than the concentrations. For example, loads and load reductions are the central issue in BMP studies that have direct links to receiving water bodies that are regulated under the Total Maximum Daily Load (TMDL) program, particularly when concerned about pollutants being deposited in slow moving systems.

Dry weather flows can contribute substantially to long-term loading. In addition, “on-line” BMPs (e.g., ponds and possibly filters) that have appreciable dry weather flows passing through them can have a reduced “capacity” for storage of wet weather pollutants. For example, pond performance may be affected by the amount of water in the pond before the event, and filters may lose some of their adsorption capacity because of pollutants and other constituents present during dry weather flows.

7.1.3 Event Mean Concentrations

The term “EMC” is a statistical parameter used to represent the flow-proportional average concentration of a given parameter during a storm event. It is defined as the total constituent mass divided by the total runoff volume. When combined with flow measurement data, the EMC can be used to estimate the pollutant loading from a given storm. The primary aim of using the EMC approach to understanding BMP efficiency is to analyze wet weather flows at a site. In most circumstances, the EMC approach provides the most useful means to quantify the pollution level resulting from a runoff event. The collection of EMC data is the primary focus of the BMP Database Project.

7.1.4 Volume Reductions

Since runoff volume reduction is directly associated with contaminant load reductions, it is a key metric used to quantify the performance of any stormwater BMP, particularly BMPs that are designed specifically to store, infiltrate, and evapotranspire captured stormwater. Accurately quantifying volume reductions requires measurements of both inflow and outflow volumes from the BMP. These volumes are typically based on continuous flow measurements over a specified duration. For BMPs without well-defined inlets or outlets, collection of paired flow measurements may not be practicable, or they may need to be approximated through indirect means such as water level measurements. In some situations, model simulations may be needed to approximate inflow or outflow volumes in order to estimate volume reductions. Refer to Section 8.4.1 for guidance on reaching appropriate conclusions regarding volume reductions through analysis of data or interpreting hydrologic model results.

7.2 Data Analysis and Underlying Principles

The following section provides guidance about the general approaches used to analyze monitoring data and briefly summarizes some of the underlying principles of recommended statistical methods. Due to the overall intent and scope of this manual, many of the methods are merely introduced. Therefore, the reader is encouraged to delve into the statistical literature and data analysis software for the specific details of approaches referenced here.

7.2.1 Descriptive Statistics

The computation of descriptive statistics is a fundamental step in exploratory data analysis. Descriptive statistics include measures of location or central tendency (e.g., mean, median), measures of spread or variability (e.g., standard deviation, interquartile range), and measures of skewness or symmetry (e.g., coefficient of skewness, quartile skew coefficient).

Two general approaches can be taken to compute descriptive statistics: parametric or non-parametric.

Exhibit 7-1 summarizes the parametric and non-parametric statistics commonly used to describe data sets. The parametric and non-parametric methods used to compute these descriptive statistics are briefly described in the sections below.

Exhibit 7-1. Common Parametric and Non-Parametric Descriptive Statistics

Statistic Category	**Parametric**	**Non-Parametric**
Measures of Location	Mean	Median
Measures of Spread	Variance, Standard Deviation	Interquartile Range, Median Absolute Deviation
Measures of Skew	Coefficient of Skewness	Quartile Skew Coefficient

Note that a dataset that is highly skewed (e.g., coefficient of skewness <-3 or >3) indicates the data do not arise from a normal distribution and may need to be transformed into a normal distribution prior to applying statistical procedures that depend on an assumption of normality. Tests of normality should be conducted to verify the transformed data fit the normal distribution.

7.2.1.1 Parametric Statistics

Parametric statistics operate under the assumption that data arise from a single statistical distribution. The specific distribution to which the data are modeled is often chosen by scientific judgment and graphical means, such as the methods described below in Section 7.2.4, and goodness-of-fit tests. The common goodness-of-fit tests are: the *Kolmogorov-Smirnov* (K-S) test and the modified Lilliefors test; the *chi-square* (χ^2) test; the Shapiro-Wilk test; and the probability plot correlation coefficient (PPCC) test.

Once a statistical distribution has been selected, the parameters of the distribution are typically estimated using one of three approaches: (1) method of moments; (2) method of maximum likelihood; or (3) method of L-moments (as described in detail in Chapter 18 of Handbook of Hydrology (Stedinger et al. 1993). While it is beyond the scope of this document to provide specific details about each of these methods, a few qualitative points are provided below:

- Method of moments: This approach utilizes the product moments of a sample to estimate the expected values of the selected distribution parameters (Devore 1995; Dingman 2002). While this method is perhaps the most well known and is the standard for estimating descriptive statistics in spreadsheet statistical software algorithms, it can produce severely biased variance and skewness estimates for small sample sizes and for samples containing a few extreme values. Because of these problems, this method is not recommended for computed descriptive statistics that are to be used to describe the underlying population distribution in order to estimate values at the tails of the distribution (e.g., 90th percentile exceedance probabilities).

- Method of maximum likelihood: Statisticians generally recommend this approach rather than the method of moments approach previously described (Devore 1995). This approach finds parameter values that maximize the joint probability of occurrence for all observed sample values (Chow et al. 1988). As with the method of moments approach, the maximum likelihood estimator can be biased if a sample size is small. However, this method is approximately unbiased when the sample size is large (Devore 1995). The difficulty with this method is that analytical formulae do not exist for every parameter in some distributions (e.g., the shape parameter of the gamma distribution), thus requiring numerical approximations (Chow et al. 1988).

- Method of L-moments: This approach utilizes probability-weighted moments and is nearly as efficient as the method of maximum likelihood, but can be computed analytically using linear combinations of ordered statistics (Hosking and Wallis 1997; Hosking 1990). In addition, the variation and skewness estimates do not suffer from the severe bias problems encountered with the method of moments because L-moments avoid squaring and cubing the data (Dingman 2002).

7.2.1.2 Non-parametric Statistics

Non-parametric statistics are fundamentally based on the ranks[1] of the data with no need to assume an underlying distribution. Non-parametric statistics do not depend on the magnitude of the data and are therefore resistant to the occurrence of a few extreme values (i.e., high or low values relative to other data points do not significantly alter the statistic). The data median is the most basic example of a non-parametric statistic. The median or 50th percentile of a dataset is the value at which half the data lie above and half the data lie below. Depending on the goals of analysis and the uncertainty of the data's underlying statistical distribution, the median may be a more appropriate measure of the central tendency of the data than the sample mean since it is less influenced by the presence of a few outliers. The median EMC may be more representative of the typical or average site storm event discharge concentration because the value is more robust in the presence of outliers, when compared to the mean. The mean EMC for a site, on the other hand, may be completely biased by a single event that had an abnormally high discharge concentration due to an anomalous point source mass release (e.g., a silt fence failing at a construction site).

7.2.2 Relevance of the Lognormal Distribution

The opportune characteristic of water quality data tending toward lognormality is that it can be easily transformed to a normal distribution by simply taking the log of each data point. This transformation allows for parametric statistical procedures that require normality assumptions to be performed. However, a goodness-of-fit test as mentioned above in Section 7.2.1.1 should be performed on the transformed data prior to conducting such parametric procedures.

The lognormal probability distribution is often used to represent environmental data because of the positively skewed nature of the data. The lognormal distribution has been shown to be a good fit for urban stormwater runoff EMC data for many constituents (EPA 1983; Harremoe 1988; Van Buren et al. 1996; Maestre et al. 2005) and this distributional fit has been justified theoretically by Chow (1954). The assumption that a population is lognormally distributed implies that the standard deviation is proportional to the mean and the data are bounded by zero.

The assumption that stormwater data and BMP effluent EMCs are lognormally distributed has been explored in a number of published studies. For example, Van Buren et al. (1996) state that the lognormal distribution may be a better estimate for pond effluent and/or for soluble constituents, an assertion supported by work conducted by Watt et al. (1989). In addition, Maestre et al. (2005) evaluated the probability distributions of the stormwater quality data in the National Stormwater Quality Database. They confirmed that lognormal distributions are very common for the constituents found in that stormwater database, with few exceptions (such as for pH).

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[1] In this context, ranks refer to the positions of the data after being sorted by magnitude.

A random variable, x, is said to be lognormally distributed if the distribution of $y = \ln(x)$ is normally distributed with a mean, μ_{ln}, and variance, σ_{ln}^2. The mathematical equation for lognormal distribution is:

$$f_x(x) = \frac{1}{\sqrt{2\pi}\sigma x} \exp\left[-\frac{1}{2}\left(\frac{lnx-\mu}{\sigma}\right)^2\right] \quad x > 0$$

Equation 7-1

Where:

μ : sample mean of the untransformed random variable x

σ^2: variance of the untransformed random variable x

x. variable of interest

The lognormal distribution parameters of x are related to the normal parameters of y with the following equations:

$$\mu = \exp(\mu_{ln} + 0.5\sigma_{ln}^2)$$

Equation 7-2

$$\sigma^2 = \mu^2 \sqrt{\exp(\sigma_{ln}^2) - 1}$$

Equation 7-3

A common misconception is that the exponential of the arithmetic mean of the log-transformed variable y is the mean of the untransformed variable x. However, $exp(\mu_{ln})$ is the geometric mean of the untransformed variable x, which is equal to the median of a lognormal random variable, not the mean. Any percentile, p_k, of x can be computed using the parameters of y as follows:

$$p_k = \exp(\mu_{ln} + z_k\sigma_{ln})$$

Equation 7-4

Where:

z_k: kth percentiles of the standard normal distribution

Refer to Appendix F for a quick reference equations for transforming between the normal and log-normal distributions.

7.2.3 Comparative Statistics and Hypothesis Tests

The field of comparative data analysis encompasses a series of tests that facilitate determining whether the descriptive statistics of two data sets are significantly different. Such analysis is directly applicable to assessing BMP performance. These methods are capable of comparing totally independent (non-paired) sets of data, such as the effluent concentrations from two different BMP studies, or dependent (paired or matched) data sets, such as the inflow and outflow concentrations from a single BMP. If inflow and outflow data appear to follow different or unknown distributions (e.g., normal or lognormal), or if either data set contains a high proportion (i.e., >15 percent) of non-detects, non-parametric tests may be more appropriate than parametric tests. Both parametric and non-parametric tests are briefly described below.

7.2.3.1 Independent Data Sets

Independent data sets can be compared using the Rank-Sum Test or the *t*-Test. The rank sum test involves joining the data sets and computing the ranks. When dealing with small data sets ($n<10$, with n being the number of sample points), the functional statistic of this test, W_{rs} is computed by summing all of the ranks of the smaller of the two data sets. For larger data sets, a second statistic, Z_{rs} is computed using W_{rs} , the sample mean, and the sample standard deviation of the combined data sets. A table is then used to assess Z_{rs}. The t-Test can only be used on normally-distributed, uncensored data sets and does not work well for small sample sizes (Helsel and Hirsch 2002). For these reasons, the Rank-Sum Test is often preferred. The difference of magnitudes of two data sets can be quantified using the Hodges-Lehmann test, which is the median of all possible pairwise differences of two data sets. The difference of the sample means is rarely of any value unless the conditions prescribed for the t-Test (uncensored, normally distributed) are met.

7.2.3.2 Paired Data Sets

Matched data sets can be compared using the Sign Test, Rank-Sign Test, and the Paired t-Test. Given two matched data sets, $\boldsymbol{x}$ and $\boldsymbol{y}$, these tests are performed solely on the difference between the two $\boldsymbol{D} = \boldsymbol{x}\text{-}\boldsymbol{y}$. The Sign Test is fully non-parametric, and therefore is often preferred. The number of elements in $\boldsymbol{D}$ that are larger than 0 (noted as S^+) is compared to the number less than 0 (noted as S^-). The Signed Rank Test is used to determine if **x** and **y** are samples of the same population; and if they are, the test is also used to determine whether the difference between the two is only in their location (e.g., median). The paired t-Test is again subject to the assumptions and stipulations associated with other t-Tests mentioned above. The paired t-statistic is computed in the following manner:

$$t_p = \frac{\bar{D}\sqrt{n}}{\sigma}$$ **Equation 7-5**

Where:

$\overline{D}$: mean

σ: standard deviation of the differences

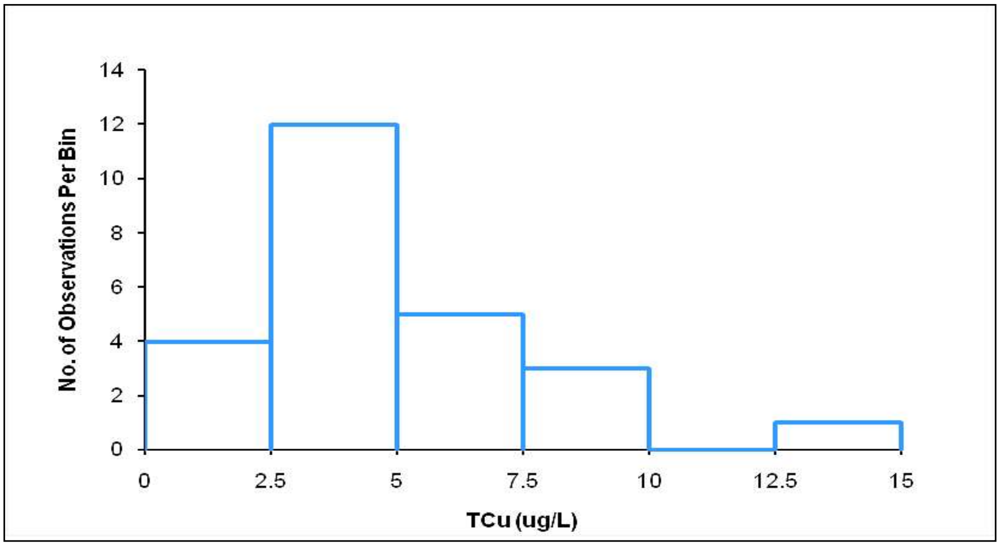
7.2.4 Graphical Data Analysis

Visualizing or graphically displaying data is an essential tool for data analysts. Not only does it provide data analysts with preliminary information about the general characteristics of a dataset, but it also enables them to perform a more comprehensive and statistically valid analysis. Four types of plots are often used to describe and visually display the characteristics of environmental data: histograms; quantile plots; scatter plots; and box plots.

7.2.4.1 Histograms

Histograms are used to visualize the empirical distribution of a single dataset by categorizing the data into bins. The number of data (frequency of occurrence) in each bin is then plotted on the dependent (Y-) axis with the bins themselves on the independent (X-) axis. This practice provides a rough estimate of the shape or symmetry of the probability density function (PDF) of the underlying distribution from which the sample data arise. Exhibit 7-2 is an example of a histogram displaying the frequency of total copper effluent concentrations (TCu) from a wetland basin. Note that the data appear to be skewed to the right (positively skewed) indicating that a lognormal distribution may be an appropriate fit for this data set.

Exhibit 7-2. Example Histogram

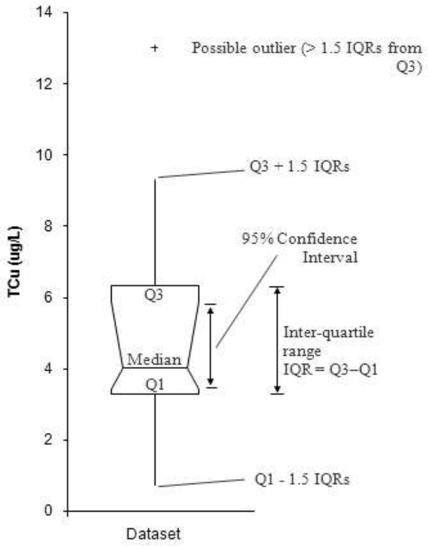


7.2.4.2 Box plots

Box plots (or box and whisker plots) provide a schematic representation of the central tendency and spread of the data. A standard boxplot consists of two boxes and two lines.

The lower box expresses the range of data from the 25th percentile (1st quartile or Q1) to the median of the data (50th percentile, 2nd quartile, Q2). An upper box represents the spread of the data from the median to the 75th percentile (3rd quartile or Q3). The total height of the two boxes is known as the interquartile range (Q3 – Q1). A "step" is 1.5 times the interquartile range. Two lines are drawn from the lower and upper bounds of the boxes to the minimum and maximum data points (respectively) within one step of the limits of the box. Asterisks or other point symbols are sometimes used to represent outlying data points. Some statistical packages, including stand alone software and third-party spreadsheet extensions, also include the confidence interval about the median as notches in the boxes about the center line or can be customized to include specific data percentiles (e.g., 5th, 10th, 90th, and 95th). Exhibit 7-3 shows a boxplot with each characteristic visually displayed.

Exhibit 7-3. Example Boxplot with Definitions



The confidence interval is shown by the location of the notches in the box plot and is based on the work of McGill et al. (1978), which recommends the following definition of the confidence interval:

$$Confidence\ Interval\ of\ Median = Median \pm 1.7\left[\frac{1.25IQR}{1.35\sqrt{n}}\right] \qquad \textbf{Equation 7-6}$$

Where:

IQR: interquartile range

n: number of samples

The upper and lower 95 percent confidence limits of the median allow the box plot to be used as a nonparametric, graphical analysis of variance. The extent to which the confidence intervals for the distributions of event concentrations at the inflow and outflow overlap gives a good indication if the medians can be considered statistically different (i.e., we can reject the null hypothesis that the inflow and outflow medians are the same). In most cases, the Kruskal-Wallis test and the Kolmogorov-Smirnov test support the results of the notched box plot. However, these hypothesis tests are generally more powerful at detecting statistical difference between two sample data sets than simply comparing the confidence intervals about the medians.

7.2.4.3 Quantile Plots and Probability Plots

Quantile plots are used to visually display data for three main reasons: (1) to compare the data distributions of two data sets (called a Q-Q plot); (2) to compare a single data set to a theoretical probability distribution (e.g., normal); or (3) to calculate exceedance frequencies. Quantile plots are constructed by ranking the sample data (i.e., observations) and then calculating the plotting position for each data point. The ranked data are placed on the x-axis and the corresponding plotting positions, or percent less thans (i.e., percentage of total data points below the value on the x-axis), are placed on the y-axis. This produces a sample approximation of the cumulative distribution function (CDF) where the probability of a random sample value being less than or equal to an observation can be directly determined. Conversely, the percent of data points exceeding a water quality threshold (i.e., percent exceedance) can be simply computed as one minus the percentage of data points less than the value on the x-axis.

Depending on the application, there are several different formulas that can be used to compute the plotting position. Helsel and Hirsch (2002) recommend using the Cunnane formula for general use rather than applying a different formula for each application:

$$p = \frac{i-0.4}{N+0.2}$$

Equation 7-6

Where:

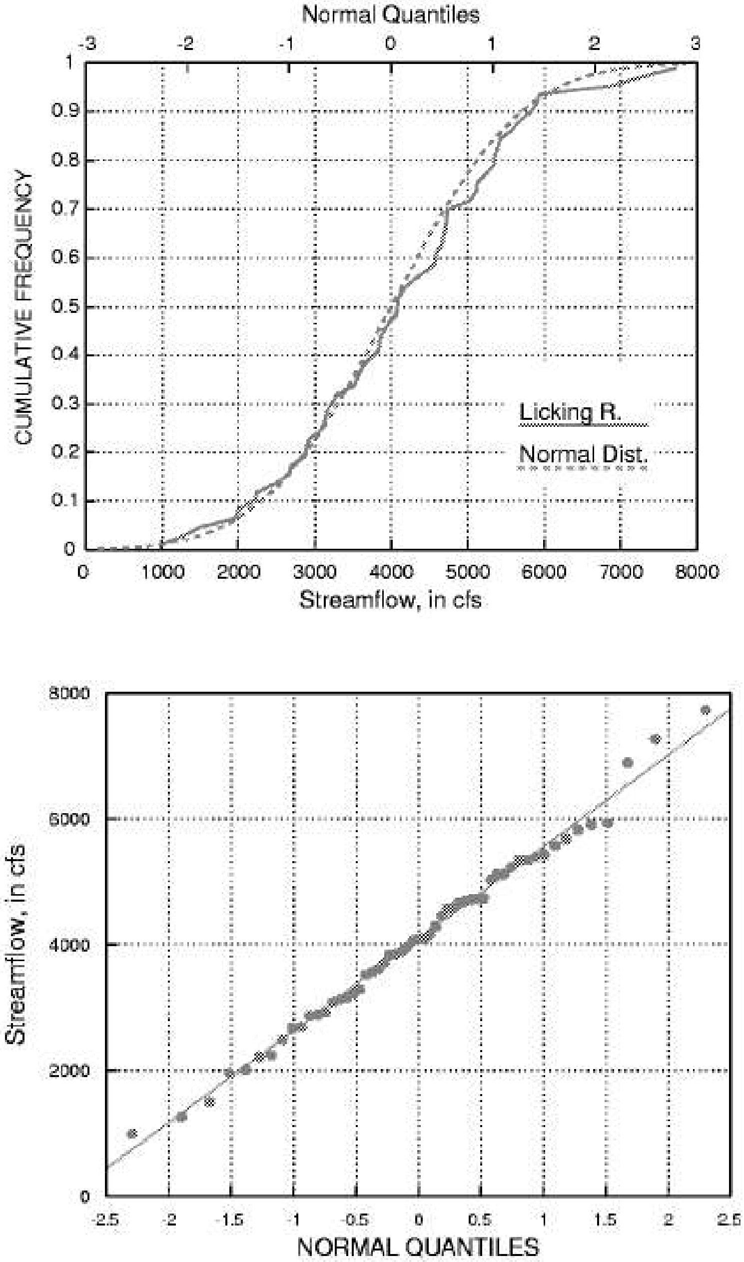
i: rank of the data point

N: number of data points

p: plotting position

Probability plots are related to quantile plots, but in this instance the quantiles of the probability distribution, instead of the percent less thans, are plotted against the observations. Both quantile plots and probability plots can be used to determine how well a dataset fits a theoretical distribution. However, rather than plotting the cumulative frequency of the data overlaid with the CDF (or plotting a histogram overlaid with the PDF) a probability plot displays the actual data plotted against quantiles of the probability distribution of interest (e.g., normal quantiles). As such, the agreement of the data with the theoretical straight line is more easily discernable than that of a curved PDF or the CDF. Exhibit 7-4 illustrates a quantile plot (top) and probability plot (bottom). Basic spreadsheet software can be used to produce quantile plots and probability plots.

Exhibit 7-4. Example Quantile Plot and Probability Plot (Helsel and Hirsch 2002)



Water quality observations do not generally form a straight line on normal probability paper, but they do (at least from about the 10th to 90th percentile level) on log-normal probability plots. This indicates that the samples generally have a log-normal distribution as described previously in this document. That means that many parametric statistical tests can often be used (e.g., analysis of variance), but only after the data is log-transformed. These plots indicate the central tendency (median) of the data, along with their possible distribution type and variance (the steeper the plot, the smaller the coefficient of variation (COV) and the flatter the slope of the plot, the larger the COV).

Multiple data sets can also be plotted on the same plot (e.g., different sites, different seasons, different habitats) to indicate obvious similarities or differences in the data sets. Most statistical methods that are used to compare different data sets require that the sets have the same variances, and many require normal distributions. Similar variances are indicated by generally parallel plots of the data on the probability paper, while normal distributions are reflected by data plotted in a straight line on normal probability paper (Burton and Pitt 2001).

Probability plots should be supplemented with standard statistical tests that determine if the data is normally distributed. These tests, at least some available in most software packages, include the Kolmogorov-Smirnov one-sample test, the chi-square goodness of fit test, and the Lilliefors variation of the Kolmogorov-Smirnov test. They are paired tests comparing data points from the best-fitted normal curve to the observed data. The statistical tests may be visualized on a normal probability plot where the best-fit normal curve (a straight line) and the observed data are both plotted. If the observed data crosses the line numerous times, it is much more likely to be normally distributed than if it only crosses the line a small number of times (Burton and Pitt 2001).

7.2.4.4 Scatter Plots

Scatter plots are the most basic of the graphical preliminary investigation tools discussed. These plots are used when discerning a potential relationship between paired data sets or the temporal trend of a single data set. For paired data, the two continuous variables are plotted against each other so that significant patterns or trends become readily apparent upon visual inspection. When looking at potential temporal trends of a single dataset, the independent variable can be time. A scatter plot matrix is useful for evaluating potential relationships between several variables at once and can be a useful starting point for multi-variable regression analysis and when evaluating the potential codependency of variables. Exhibit 7-5 is an example scatter plot matrix.

Exhibit 7-5. Example Scatterplot Matrix of Potentially Related Variables

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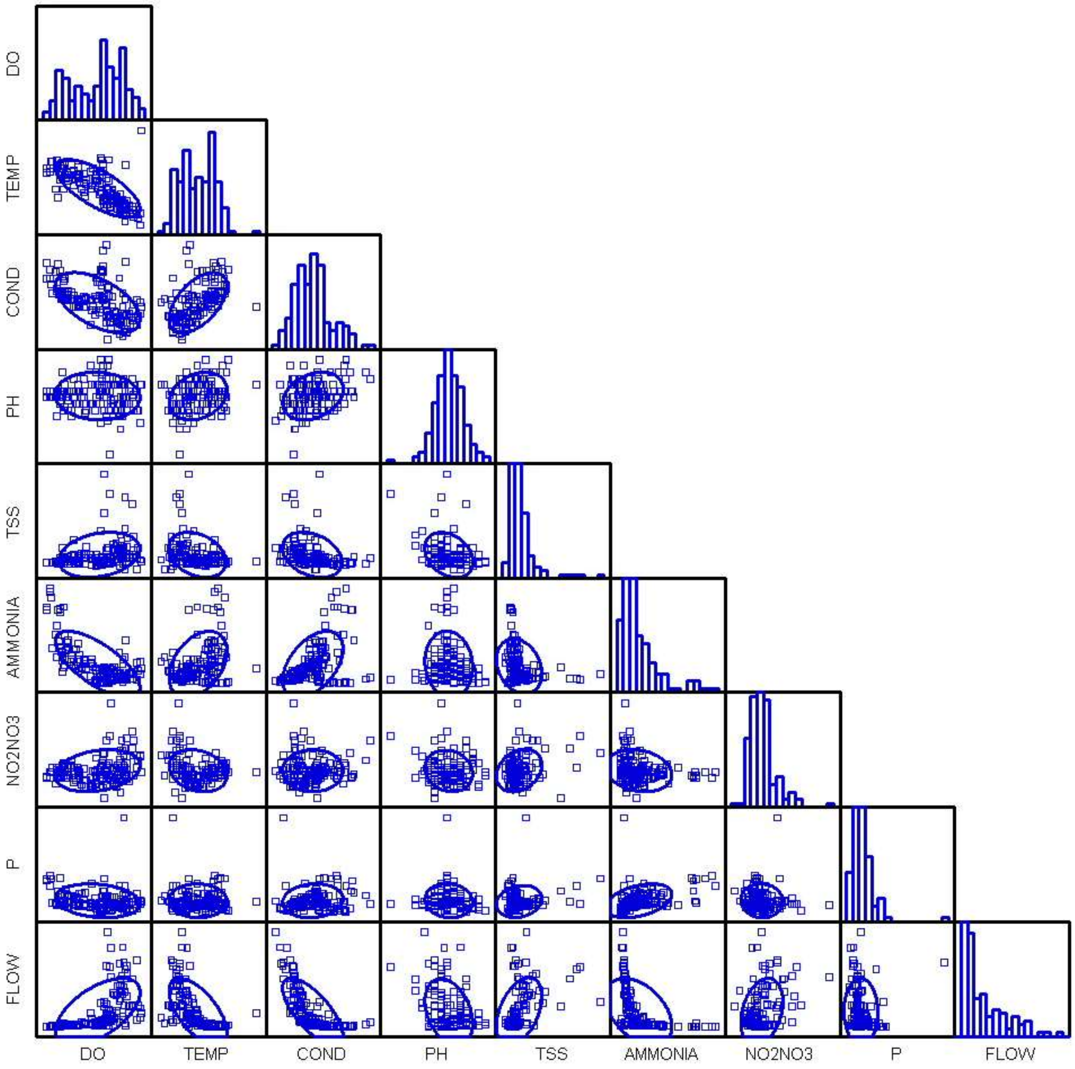

7.2.5 Analysis of Censored Data

Censored data, or nondetects, include values reported to be only above or below an analytical reporting limit[2]. Nondetects in water quality data are ubiquitous and arise from different

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[2] The terms “reporting limit” and “detection limit” are intentionally used loosely and interchangeably in this chapter. While there is clearly a difference between these values—a reporting limit (or quantitation limit) is a threshold based on a measure of the variability or noise inherent in the laboratory process, while a detection limit is a threshold below which measured values are not considered statistically different from a blank signal (Helsel 2005)—it has become commonplace to use either term when referring to nondetects. However, some laboratories will report values between the method detection limit and the laboratory reporting limit. In these

reporting limits based on changes in analytical methods, laboratories, or sample variability. If nondetects are not carefully considered when analyzing data, estimated summary statistics may become biased and nonrepresentative of the monitored site (Helsel 2005).

Four approaches are often utilized to handle nondetects: (1) simple substitution; (2) maximum likelihood estimation (MLE); (3) regression on order statistics (ROS); and (4) Kaplan-Meier (K-M). Each of these methods is briefly described in the sections below.

7.2.5.1 Simple Substitution

Simple substitution replaces all nondetect values with a constant value, such as zero, the detection limit, or half the detection limit. There is no theoretical or mathematical justification for the practice, yet it remains widely used. By substituting constant values, the distribution of the data (i.e., histogram) is altered and the overall variability is reduced. Estimates of the mean and median may become biased high or low depending on the level of censoring and the substitution method employed. It is strongly recommended that simple substitution is avoided, especially when the level of censoring exceeds 5 to 10 percent of observed data. If simple substitution must be performed, the only reasonable value to use is half of the detection limit, as the use of zero or the detection limit can cause more severe bias in computed summary statistics.

7.2.5.2 Maximum Likelihood Estimation (MLE)

With the MLE method, both the censored and uncensored data are assumed to follow a theoretical distribution (as discussed above, the lognormal is often a good choice for water quality data). Summary statistics are then computed as the values that maximize the log-likelihood function (see Helsel 2005 for details). After being first introduced by Hald (1949) and Cohen (1950), maximum likelihood estimators for estimating the statistics of censored data sets have been refined to handle multiple detection limits (Cohen 1976), and several researchers have developed bias-corrected (Cohn 1988; Shumway et al. 2002; Sharma et al. 1995) and robust (Singh and Nocerino 2001; Kroll and Stedinger 1996) MLE formulations.

7.2.5.3 Regression on Order Statistics (ROS)

ROS is a category of robust methods used to estimate descriptive statistics of censored data sets that utilize the normal scores for the order statistics (Shumway et al., 2002). [Normal scores, (also known as Z-scores or z-statistic), are the inverse of the standard normal distribution.] The ROS is a plotting position method developed by Hirsch and Stedinger (1987) and later refined by Helsel and Cohn (1988) for water quality data. In this method, plotting positions are based on conditional probabilities and ranks, where the ranks of the censored (below detection) and uncensored data (above detection) related to each detection limit are ranked independently. After plotting positions for the censored and uncensored

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cases, Helsel (2005) recommends recensoring the in-between values as <RL and then use a method that can handle multiple detection limits such that the technique accounts for the fact that the RL>DL.

values have been calculated, the log-transformed uncensored values are plotted against the z-statistic corresponding to the plotting position. The best-fit line of the known data points is derived. Using this line and the plotting positions for the uncensored data, the values for the censored data can be extrapolated. The complete "filled in" data set can then be used to estimate descriptive statistics—either by transforming all values back to the original units and computing the statistics (non-parametric formulation) or by computing the statistics in the log-transformed units (parametric formulation) and using lognormal reconversion formulas. Refer to Helsel (2005) or Helsel and Cohn (1988) for details.

7.2.5.4 Kaplan-Meier (K-M)

The K-M method is the standard method for estimating summary statistics for censored survival data (Helsel 2005). It is a completely non-parametric method that utilizes the ranks of the data to estimate "survival probabilities." In the context of water quality data, the survival probability is the probability that a data point would occur below the next incremental concentration given the number of data at or below that concentration or detection limit. Since this method is designed for right-censored data, all observations must be subtracted from an arbitrary value that is higher than the largest observation before it can be used. This transformation results in an empirical cumulative distribution function for the dataset. See Helsel (2005) for details.

7.2.5.5 Recommended Approach for Handling Nondetects

Of the methods described herein, the K-M method is the most robust method for calculating percentiles and works well on both small and large data sets; however, it cannot be used if the level of censoring is greater than 50 percent. Estimates of the mean are biased high using this approach if the lowest reported values are nondetects, which is typically the case. The variance and standard deviation tend to be sensitive to the presence of extreme values in the data set (Helsel 2005). For these reasons, the K-M method is not recommended for general use, particularly when estimates of the mean and its confidence interval are desired.

The MLE and ROS approaches are both useful and can be equally robust and accurate methods for estimating summary statistics. They both require that a distribution be assumed and both have robust and fully parametric formulations. When the distributional assumption is valid, the MLE methods can be more precise, but these methods require larger sample sets ($n \geq 50$) to estimate unbiased summary statistics using the parametric formulation. Probability plotting, as used in the ROS method, is less precise but handles small data sets better. The ROS method is more straight-forward than the MLE, does not require numerical approximations, and can be easily programmed into spreadsheets. As such, the ROS is generally preferred. Many statistical software packages include one or both methods. The ProUCL software package is available free from the Environmental Protection Agency and can be used to compute summary statistics using the ROS method (see http://www.epa.gov/esd/tsc/software.htm).

7.2.6 Bootstrap Methods

Bootstrap methods are a class of data resampling procedures used to estimate summary statistics and their accuracy (standard error). Originally developed by Bradley Efron in 1979, many variations and improvements have been made and the number of applications has grown significantly (Efron and Tibishirani 1993; Chernick 1999). The basic bootstrap method includes sampling from the data set with replacement, calculating the desired descriptive statistics from the sampled data, and repeating several thousand times. The steps of the bootstrap estimation method are described below:

1) Take a sample of size n with replacement (the sampled data point remains in the data set for subsequent sampling) from the existing data set and compute the descriptive statistic, θ_i, from the sampled data. [Singh et al. (1997), recommend *n* be the same size as the original data set.]

2) Repeat Step 1 independently *N* times (e.g., 10,000) each time calculating a new estimate for θ_i.

3) Calculate the bootstrap estimate θ_B by averaging the θ_i's for i=1 to *N*

Fundamentally, this bootstrap procedure is based on the Central Limit Theorem, which suggests that even when the underlying population distribution is non-normal, averaging produces a distribution more closely approximated with the normal distribution than the sampled distribution (Devore 1995).

The standard error, $\hat{se}_b$, of the bootstrap estimates, θ_B, is calculated as:

$$s\hat{e}_B = \left[\sum_{i=1}^{N} \left(\frac{(\theta_i - \theta_B)^2}{(N-1)} \right) \right]^{1/2}$$ **Equation 7-7**

There are a number of benefits to using the bootstrap method to estimate summary statistics rather than other standard techniques. First, the statistical distribution of the underlying population need not be assumed when using this method. Secondly, the bootstrap method provides more robust estimates of parametric statistics when underlying distribution can be assumed. Lastly, the bootstrap method allows one to compute the accuracy of statistical estimates even when no analytical formula exists (e.g., standard error of the median). Several methods for calculating confidence intervals, or the reliability of an estimate, are also available. Refer to Efron and Tibishirani (1993) for more information.

As with any statistical analysis technique, small data sets can be a problem with the bootstrap. Small data sets underestimate the true variability of the underlying distribution and this underestimation can become magnified with the bootstrap due to multiple repeated values collected during resampling (Chernick 1999). Therefore, as a word of caution, for small data sets (e.g., n<30), the bootstrap may produce inaccurate estimates of population statistics. In these cases, especially when estimating confidence intervals or exceedance frequencies, parametric methods may be more reliable than the bootstrap, particularly if the data reasonably fit the parametric distribution of interest.

7.3 Error Analysis and Measurement Accuracy

In addition to random uncertainty associated with estimating summary statistics, there are unavoidable sources of error in individual measurements or observations. Sources of measurement error can be associated with the precision of the measuring instrument, the accuracy of the calibration, and the care with which the measurement is made. If the latter two sources of error are minimized or removed, the uncertainty in the measurement is generally on the same order of magnitude as that of the smallest numerical value that can be estimated with the measuring instrument (usually expressed as a percent, or relative error). The true value of that uncertainty typically falls in a range of values that reflect the experimental uncertainty of the measurement. Calculating the mean of multiple measurements (i.e., duplicates) can provide a better estimate of the true value if the measurement errors are random in nature and not systematic.

Problems with instrument precision and/or calibration as well as inaccuracies in the measuring process can lead to indeterminate (random) errors. The magnitude of these indeterminate errors will randomly vary with repeated measurements. There are several ways random errors can be introduced, including operator error, variation in the conditions in which the measuring process is conducted, and the variability of the measuring instrument. QA/QC methods in both the field and laboratory attempt to quantify and control random errors through the use of duplicate samples and blank samples. Laboratory control charts are used to document process results such that adjustments can be made to maintain analytical errors within acceptable limits.

Determinate (systematic) errors have an algebraic sign and magnitude and result from a specific cause introducing the same error into every measurement. Determinate errors are more serious than indeterminate errors because taking the average of multiple measurements cannot reduce their effects. This is because determinate errors have the same sign and magnitude, which prevents positive and negative errors from off-setting each other. Causes of this type of error can include operator bias, (consistent) operator error such as incorrect reading of the instrument, or improper calibration of the measuring instrument.

7.3.1 Expressing Errors

Absolute and relative methods are the standard forms for expressing errors. Absolute error is expressed as a range of values reflecting the uncertainty in the measurement and is reported in the same units as the measurement. Measured values followed by the plus or minus sign express the absolute error.

Relative (or fractional) error is expressed as the ratio of the uncertainty in the measurement to the measurement itself. This is difficult to estimate, because it is a function of the true value of the quantity being measured, which is unknown. Typically this error estimate utilizes the measured value as the “true” value.

The type of measurement and instrumentation can provide an indication of the appropriate form of expressing errors. For example, a pressure probe used to measure depth of flow is likely to have the accuracy of the instrument expressed as a relative percent, while readings on a staff gage would have an absolute error related to the markings on the gage. In these instances the reported depth measurements would be expressed in the same manner as the precision of the measuring instrument.

7.3.2 Propagation of Errors

Quite often, measurements taken of one or more variables are used in equations to calculate the value of other variables. For example, to calculate the area of a rectangle, the length and width are usually measured. To calculate the volume of a cube, the length, width, and height are measured. Each measurement has a potential error associated with it and, as a result, the variable calculated from the combination of individual measurements will also contain some error. The magnitude of the error in the calculated variable can be of a different order than the error associated with any one of the measurements, depending on the algorithm that describes their relationship.

7.4 Performance of BMP and BMP Systems

Previous sections outlined statistical methods to generally analyze water quality data. This section gives guidance on how to apply those methods to evaluate BMP performance.

The efficiency of stormwater BMPs—how well a BMP or BMP system removes pollutants or results in acceptable effluent quality—can be evaluated in a number of ways. An understanding of how BMP monitoring data will be analyzed and evaluated is essential to establishing a useful BMP monitoring study. When analyzing efficiency, it is convenient to classify BMPs according to one of the following four distinct categories:

1) BMPs with well-defined inlets and outlets whose primary treatment depends upon extended detention storage of stormwater (e.g., retention (wet) and detention (dry) ponds, wetland basins, underground vaults).

2) BMPs with well-defined inlets and outlets that do not depend upon significant storage of water (e.g., sand filters, swales, buffers, structural "flow-through" systems).

3) BMPs that do not have a well-defined inlet and/or outlet (e.g., full retention, infiltration, porous pavement, grass swales where inflow is overland flow along the length of the swale).

4) Widely distributed or scattered BMPs where studies of efficiency use reference watersheds to evaluate effectiveness (e.g., catch basin retrofits, education programs, source control programs).

All four of the above categories can also include evaluations to measure BMP efficiency as described below and further discussed in Chapter 8 of this manual.

7.4.1 Comparative Measures of BMP Efficiency

Quantifying the efficiency of BMPs has often centered on examinations and comparisons of "percent removal" defined in a variety of ways. BMPs do not typically function with a uniform percent removal across a wide range of influent water quality concentrations. For example, a BMP that demonstrates a large percent removal under heavily polluted influent conditions may demonstrate poor percent removal where low influent concentrations exist. The decreased efficiency of BMPs receiving low concentration influent has been demonstrated and it has been shown that in some cases there is a minimum concentration achievable through implementation of BMPs for many constituents (Schueler 2000; Minton 2005). Percent removal alone, even where the results are statistically significant, often does not provide a useful assessment of BMP performance.

Exhibit 7-6 provides an overview of the various methods historically used to evaluate BMP performance, and Appendix B provides more detailed discussion of these individual techniques. This chapter focuses on applying the effluent probability approach to evaluate BMP efficiency, which is the approach used by the BMP Database.

Exhibit 7-6. Summary of Historical, Alternative, and Recommended Methods for BMP Water Quality Monitoring Data Analysis

Category	Method Name	Recommendation	Comments	Details
Recommended Method	**Effluent Probability Method**	**Method recommended in this guidance manual.**	**Provides a statistical view of influent and effluent quality.**	Section 7.4.4
Historical Methods	Efficiency Ratio (ER)	Not recommended as a stand-alone assessment of BMP performance. More meaningful when statistical approach is used.	Most commonly used method to date. Most researchers assume this is the meaning of "percent removal." Typical approach does not consider statistical significance of result.	Appendix B1.2
	Summation of Loads (SOL)	Not recommended as a stand-alone assessment of BMP performance. More meaningful when statistical approach is used.	Utilizes total loads over entire study. May be dominated by a small number of large events. Results are typically similar to ER method. Typical approach does not consider statistical significance of result.	Appendix B1.3
Alternative Methods	Percent Removal Exceeding Irreducible Concentration or Relative to WQ Standards/Criteria	Not recommended. May be useful in some circumstances	Typically only applicable for individual events to demonstrate compliance with standards.	Appendix B1.8
	Relative Efficiency	Not recommended. May be useful in some circumstances	Typically only applicable for individual events to demonstrate how well a BMP performs relative to what that BMP is theoretically or empirically able to achieve (as determined from another method).	Appendix B1.8
	Multi-Variate and Non-Linear Models	Possible future use	Additional development of methodology based on more complete data sets than are currently available.	Section 7.4.2

Various historical methods used to evaluate BMP performance are not recommended for use. These methods are as follows:

- Regression of loads (ROL): The assumptions of this method are very rarely valid. This method cannot be universally applied to monitoring data (refer to Appendix B1.4 for more detail).
- Mean Concentration: In this method, it is difficult to "track" the slug of water through BMP without extensive tracer data and hydraulic study. The results are only for one portion of the pollutograph (refer to Appendix B1.5 for more detail).
- Efficiency of Individual Storm Loads: In this method, the storage of pollutants is not taken into account. This method gives equal weight to all storm event efficiencies (refer to Appendix B1.6 for more detail).
- "Lines of Comparative Performance©": This method is not statistically valid due to self-correlation (refer to Appendix B1.8.3 for more detail).

This chapter focuses on applying the effluent probability approach to evaluate BMP efficiency, which is the approach used by the BMP Database.

7.4.2 Multivariate and Non-Linear Model

Reporting efficiency as a percent removal that is calculated based on the difference between influent and effluent concentrations always makes a BMP treating higher strength influents appear to be more efficient than one treating weaker influents, that is if both BMPs are achieving the same effluent quality. A more useful descriptor of efficiency accounts for the fact that weaker influents are more difficult to treat than concentrated ones. A multivariate equation that includes corrections to compensate for this phenomena or a non-linear model may be worth considering for reporting efficiency.

A model that approaches pollutant removal in a manner similar to the reaction rates for complex physical and chemical batch and plug-flow processes may be useful. To date, calibration of such a model for all but the most elementary situations (e.g., settling of solids in relatively simplistic flow regimes) is difficult given the complexity of the real-world problem. As more high quality data become available, other approaches to evaluating BMP efficiency may become apparent.

Currently, effluent quality, as discussed below, is the best indicator of overall BMP performance.

7.4.3 Reference Watershed Methods

Many BMPs do not allow for comparison between inlet and outlet water quality parameters. In addition, it is often difficult or costly to monitor a large number of specific locations if there are many BMPs being installed throughout a watershed (e.g., retrofit of all catch basins). In these cases, a reference watershed is often used to evaluate the effectiveness of a given BMP or multiple BMPs of the same type. A primary reason to use a reference watershed is to overcome the problem associated with some BMPs that have no clearly defined inlet or outlet point at which to monitor water quality. BMPs with this challenge may include non-structural BMPs, porous pavements, and infiltration practices. The BMP Database allows for a watershed and all its associated data to be identified for use as a reference watershed.

The difficulty in determining the effectiveness of a BMP using a reference watershed approach stems from the large number of variables typically involved. When setting up a BMP monitoring study, it is advantageous to keep the watershed characteristics of the reference watershed and the test watershed 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 effectiveness of a BMP based on a reference watershed, an accurate accounting of the variations between the watersheds, and operational and environmental conditions is needed. The BMP Database explicitly stores some of the key parameters required for normalization of watershed and environmental conditions.

The most obvious parameter used to normalize watershed characteristics is area. If the ratio of land uses and activities within each watershed is identical in both watersheds then the watershed area can be scaled linearly. The loads found at each downstream monitoring station for each event can be scaled linearly with area as well. Difficulty arises when land use in the reference watershed is not found in the same ratio. In this case, either the effects of land use must be ignored 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. In many cases, the differences in land use can be ignored (e.g., between parking lots with relatively small but different unpaved areas). The effect of the total impervious area is relevant and should always be reported in monitoring studies. The ratio of the total impervious areas can be used to scale event loads. Scaling the loads based on impervious areas is best used where the majority of pollutants come from runoff from the impervious areas (e.g., parking lots), or where the contaminant of interest results primarily from deposition on impervious surfaces [e.g., total suspended solids (TSS) in a highly urban area]. Methods that attempt to determine BMP performance from poorly matched watersheds yield poor results at best. As the characteristics of the two watersheds diverge, the effect of the BMP is masked by the large number of variables in the system; the noise in the data becomes greater than the signal.

The analysis of BMPs utilizing reference watersheds also requires incorporation of operational details of the system (e.g., frequency of street sweeping, type of device used, device setup). Monitoring studies should always provide the frequency, extent, and other operational parameters for nonstructural BMPs. If the BMP is an alteration of the frequency of a certain practice, the system can be viewed in two ways: (1) as a control/test system; or (2) as a series of data aimed at quantifying the continuous effect of increasing or decreasing BMP frequency. In the first case, the BMP can be analyzed in a manner similar to other BMPs with reference watersheds. In the second case, the loads realized at the monitoring stations need to be correlated with the frequency using some model for the effectiveness of the practice per occurrence.

7.4.4 Effluent Probability Method

The most useful approach to quantify BMP efficiency is to first determine if the BMP is providing treatment (that the influent and effluent mean EMCs are statistically different from one another) and then examine a cumulative distribution function of influent and effluent quality or a standard parallel probability plot.

Before any efficiency plots are generated, appropriate non-parametric (or if applicable parametric) statistical tests should be conducted to determine if any perceived differences in influent and effluent mean EMCs are statistically significant. (The level of significance should be calculated and reported using an appropriate hypothesis test, instead of just noting if the result was significant; assume a 95 percent confidence level.)

Effluent Probability Method is straightforward and directly provides a clear picture of the effluent water quality, which is the ultimate measure of BMP effectiveness. Curves of this type are the single most instructive piece of information that can result from a BMP evaluation study. The authors of this manual strongly recommend that the stormwater industry accept this approach as a standard "rating curve" for BMP evaluation studies.

The most useful approach for examining these curves is to plot the results on a standard parallel probability plot as shown in Exhibits 7-7 through 7-9 below. A normal probability plot should be generated showing the log-transform data of both inflow and outflow EMCs for all storms for the BMP. If the log-transformed data deviates significantly from normality, other transformations can be explored to determine if a better distributional fit exists.

Exhibits 7-7 through 7-9 show three types of results that can be observed when plotting pollutant reduction observations on probability plots. These data were taken from the Monroe Street Wet Detention Pond Study in Madison, WI, collected by the United States Geological Survey (USGS) and the Wisconsin Department of Natural Resources. Exhibit 7-7 for suspended solids (SS) (particulate residue) shows that SS are effectively reduced by the BMP across the entire range of the influent distribution. In contrast, Exhibit 7-8 for total dissolved solids (TDS) (filtered residue) shows poor removal of TDS for nearly the entire range of influent concentrations, as would be expected for a wet detention pond. In this case, the "percent removal" (ER Method) for TDS would be close to zero. Exhibit 7-9, however, shows a wealth of information that is not available from simple statistical numerical summaries. In this plot, filtered chemical oxygen demand (COD) is seen to be poorly removed for low concentrations (less than about 20 mg/L), but the removal increases substantially for higher concentrations. Note that while influent and effluent percentiles are not necessarily paired, the rank order of concentrations was similar for both influent and effluent distributions for all three pollutants (Burton and Pitt 2001).

Exhibit 7-7. Probability Plot for Suspended Solids

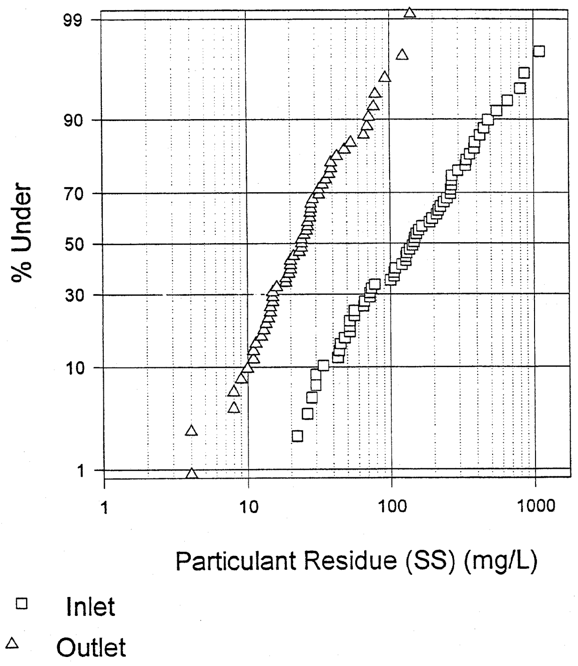


Exhibit 7-8. Probability Plot for Total Dissolved Solids

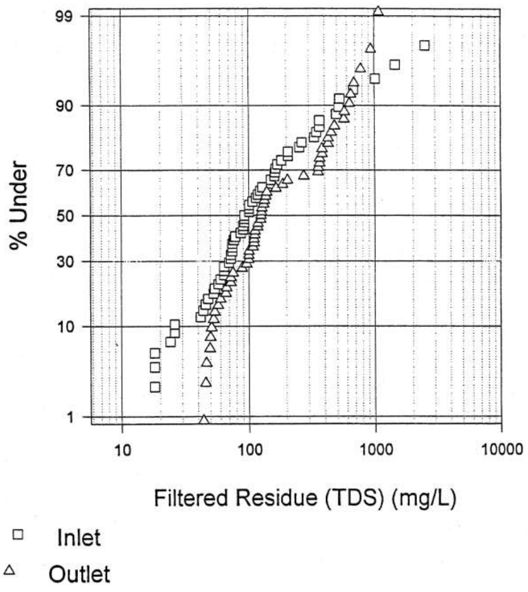
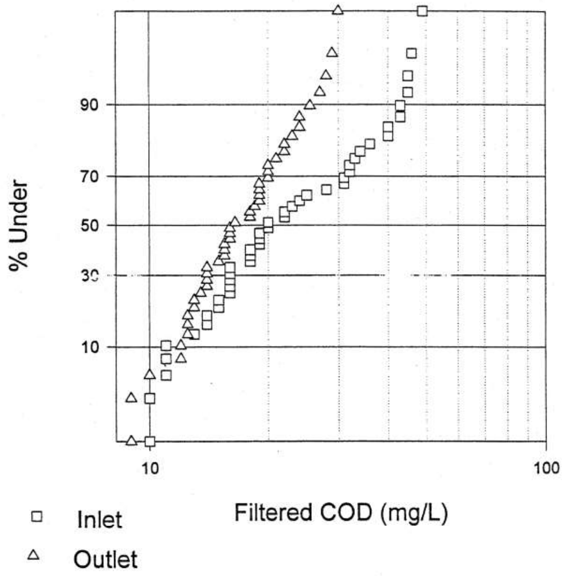


Exhibit 7-9. Probability Plot for Chemical Oxygen Demand



7.4.5 Statistical Measures Employed by the BMP Database

A variety of methods used to evaluate the efficiency and effluent quality of BMPs have already been explored in this Manual. A discussion of data preparation and the statistical and graphical approaches used to evaluate efficiency and effluent quality are presented in this section.

Each BMP study in the BMP Database contains a "Detailed Statistical Analysis Report" (DSAR) for each monitored parameter. The DSAR provides guidance about the efficiency of the treatment practice. The DSAR contains the following elements:

1) Arithmetic estimate of the mean inflow and outflow EMC.

2) Bootstrap estimate of the mean inflow and outflow EMC.

3) Data plots (time series plot; box plot; and probability plot).

4) Summary of distributional characteristics (Shapiro-Wilks W-test and Lilliefors test).

5) Hypothetical test results for non-parametric analysis (Mann-Whitney test).

6) Hypothetical test results for parametric analysis (t-Test on raw and log-transformed data).

7) Test of Equal Variance (Levene Test on raw and log-transformed data).

For the International BMP data sets, it is assumed that both influent and effluent EMCs for most constituents fit well with the log-normal distribution. This assumption appears to be a good approximation of the distribution of water quality data in most cases. A number of parameters are generally not assumed to fit a lognormal distribution based on analysis of BMP performance data: pH; dissolved oxygen; bacterial counts (e.g., fecal coliform); and turbidity due to the nature of the methods used to quantify these parameters.

For dissolved and particulate water quality constituents, the assumption of log-normality of the data set has been determined by exploring samples of the data in three ways:

1) A comparison between the non-parametric and parametric analyses of variance (p values within 10 percent) has been conducted to assess differences found using the different methods.
2) The Pearson Chi-square test has been conducted and, where there are an appreciable number of data points available, the results of the Pearson Chi-square test indicate that the normal approximation is a good estimate of the central tendency and the distribution of the logarithm of the event concentrations. In cases where a small number of data points are present, there is often very little confidence that either the transformed or non-transformed data are well represented by a normal distribution.
3) Graphical probability plots of influent and effluent have been examined.

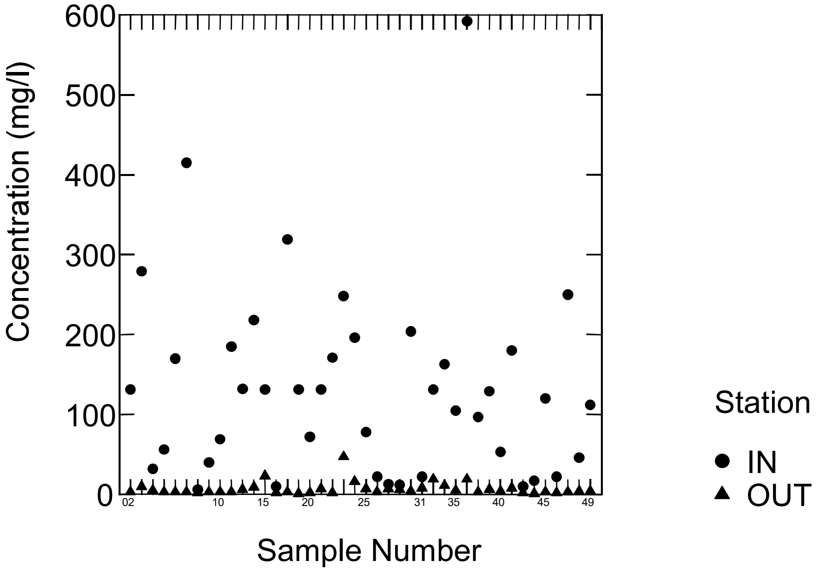
For many summary statistics contained in the BMP Database log-normality was assumed and is typically more appropriate than assuming normality. However, in some specific cases this log-normality may not be appropriate and alternative summary statistics, such as non-parametric statistics, should be chosen. Data plots and goodness-of-fit results should be evaluated before using any particular summary statistics from the BMP Database.

The following provides an overview of the information provided in the periodic statistical summary reports contained in the BMP Database.

7.4.5.1 Influent and Effluent Scatter Plots

Plots showing event concentrations of influent and effluent are included in the DSAR. These plots are compiled based on data collected for each storm. Water quality sample concentrations are identified on a linear scale with inflows and outflows identified using different symbols. These graphs are provided to give an indication of the number of samples collected over the course of the study, which events had paired samples, and the relative difference between influent and effluent concentrations. The sample number indicates each period where samples were collected. This period typically coincides with a storm event; however, this is not always the case. Samples collected during a single dry period are indicated with a separate sample number. If more than one sample is collected at a single location during a period, it is indicated by two of the same symbol at a single sample number. All samples are shown in chronological order. The influent/effluent scatter plot for the Tampa Office Pond (1994 to 1995) for TSS is presented in Exhibit 7-10.

Exhibit 7-10. Linear Influent/Effluent Plot for TSS (Tampa Office Pond 1994-1995)



7.4.5.2 Box Plots

Box plots were discussed as a graphical data analysis tool in Section 7.2.4.2. Box plots are summarized for inflow and outflow concentrations for each BMP study in the Database. A discussion of potential ways of interpreting side-by-side box plots provided in the DSAR is provided below.

There are four primary behaviors observed when comparing distributions of inflow and outflow event concentrations using box plots. These are shown in the following examples:

1) Positive or negative differences where the confidence intervals do not overlap (Exhibit 7-11 and 7-12): This indicates that the median EMCs may not be statistically different. However, if the confidence intervals are nearly overlapping, a more powerful statistical test (e.g., Kruskal-Wallis) should be conducted to determine whether the medians are significantly different.

2) Differences where the confidence intervals appreciably overlap (Exhibit 7-13): In this case, the confidence interval about the median inflow overlaps the confidence interval about the median outflow. The graphical non-parametric analysis of variance (i.e., the notched box plot) indicates that the observed differences in the median are not statistically significant at the 95 percent confidence level.

3) Positive or negative differences where the confidence intervals marginally overlap (Exhibits 7-14 and 7-15): A more powerful statistical test (e.g., Kruskal-Wallis) should be conducted to determine whether the median EMCs are significantly different.

4) Other Cases (Exhibit 7-15): In some cases the 95 percent confidence limit is either in excess of the third quartile or less than the first quartile or both (see Exhibit 7-15). These cases correspond to a distribution of values that is strongly skewed and/or has a low number of samples. The examination of the probability plot may help shed light as to why the confidence limit is outside of the interquartile range.

Exhibit 7-11. Statistically Significant Positive Efficiency as Indicated Through the Box Plot

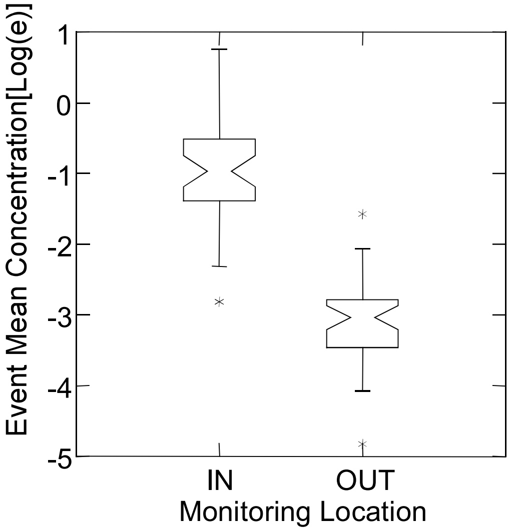


Exhibit 7-12. Statistically Significant Negative Efficiency as Indicated Through the Box Plot

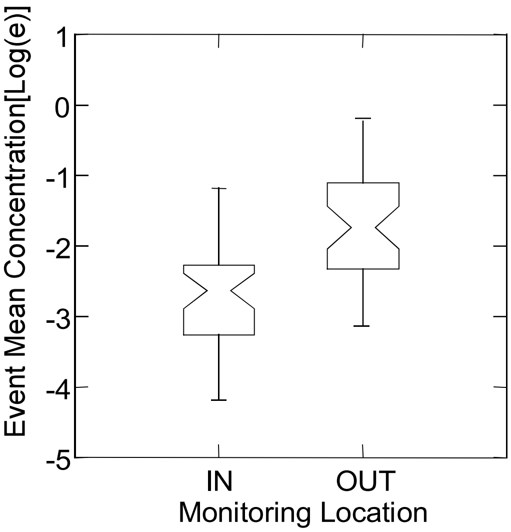


Exhibit 7-13. Statistically Ambiguous Difference in Median Event Concentration as Indicated Through the Box Plot

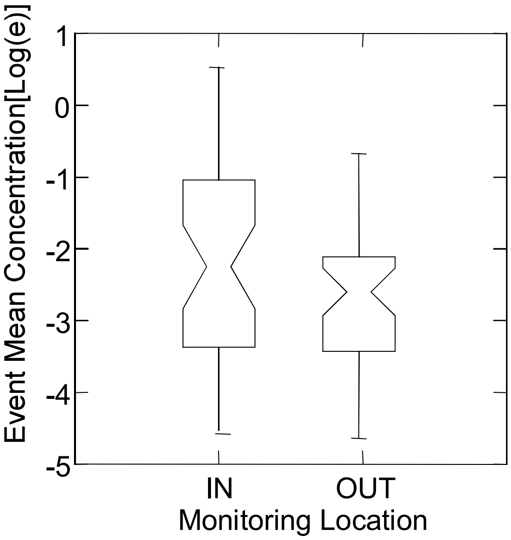


Exhibit 7-14. Marginally Statistically Significant Positive Efficiency as Indicated Through the Box Plot

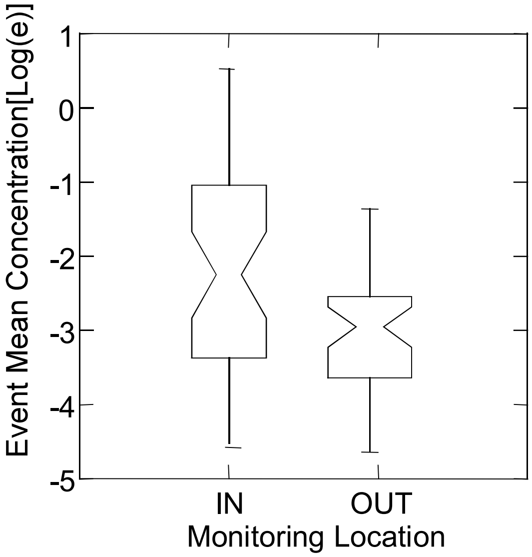
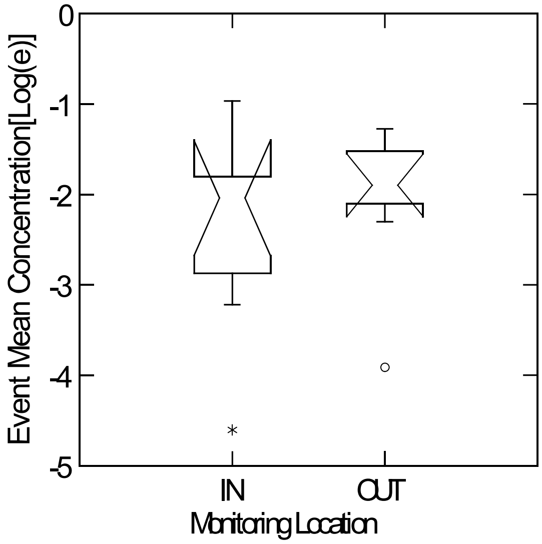


Exhibit 7-15. Example Box Plot Demonstrating Quartiles That Are Inside the Confidence Interval Due to the Small Number of Events Monitored



7.4.5.3 Probability Plots

In accordance with the recommended Effluent Probability Method discussed above, probability plots are included in the DSAR for each BMP and parameter analyzed. Probability plots were chosen for graphical analysis of the water quality concentration data because of the plot's ability to quickly and succinctly relay information about the following:

1) How well data, or transformed data, at each monitoring station are represented by the normal distribution.

2) The mean and standard deviation of the normal distribution and the value of any specific quantile. The slope of the normal approximation is an indication of the magnitude of the standard deviation (straight line); the x-intercept demonstrates the log mean concentration.

3) The relationship between two distributions across the range of quantiles.

4) The presence of any significant outliers.

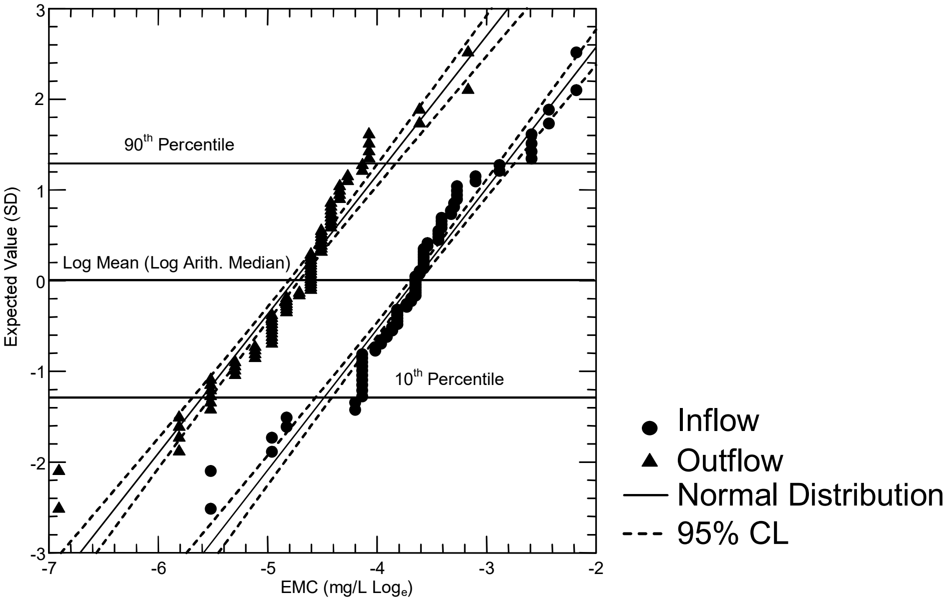
5) The width of the 95 percent confidence interval of the normal approximation.

Note that the quantiles of the inflow and effluent concentrations may not be matched data points as this only occurs if the rank correlation (Spearman's Rho) is precisely 1. For low rank correlations, the 10 percent exceedence concentration in the inflow distribution may not be from the same storm as the 10 percent exceedence concentration in the outflow. Therefore, care must be exercised to not interpret these plots as plots of individual data pairs.

Two sample probability plots are given below in order to explain the range of behaviors that can be encountered when analyzing water quality data. When overlaying normal probability plots for two data sets (typically EMCs from inflow and outflow from a BMP), the results exhibit five primary types of behavior that are described below.

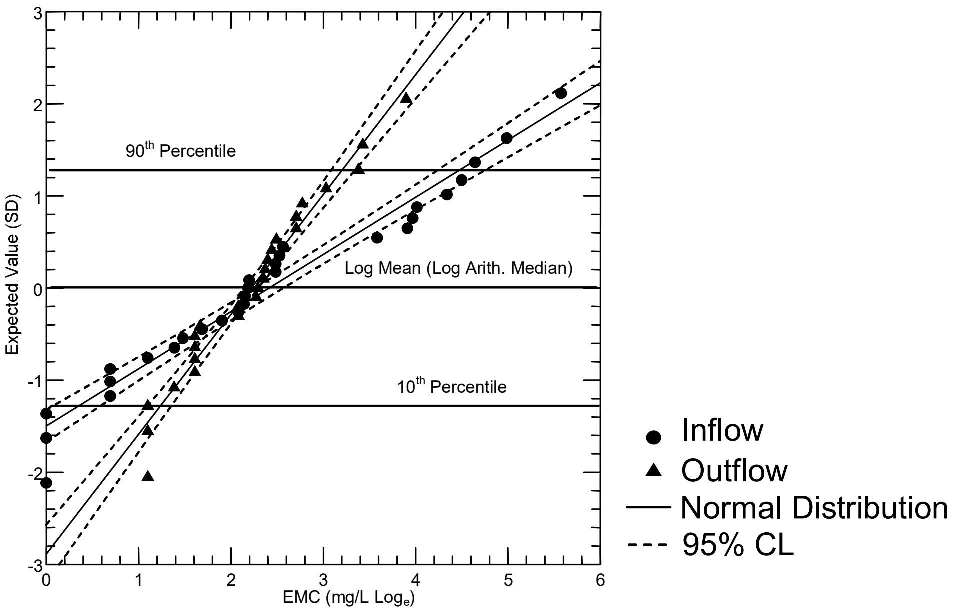
1) The first example (Exhibit 7-16) demonstrates the behavior of two transformed data sets (one from the inflow and one from the outflow of a BMP) that have very similar standard deviations (slope of the normal probability plot) and a uniform difference across the range of quantiles when plotted on a logscale. This indicates that there is a significant difference not only in the log of the mean EMCs, but a significant difference across any given quantile.

Exhibit 7-16. Example Normal Probability Plot for TSS
(Tampa Office Pond 1994-1995)



2) The second example (Exhibit 7-17) shows distributions of TSS inflow and outflow EMCs with similar means and different standard deviations. The regression lines cross near the x-intercept, which is the expected value at the mean. This behavior demonstrates negative removal at lower quantiles and positive removal at higher quantiles. This suggests that the BMP may have a minimum effluent concentration that can be achieved, particularly if the intersection point occurs at a low concentration.

Exhibit 7-17. Example Normal Probability Plot for TSS (Tampa Office Pond 1993-1994)



The other three behaviors that are observed when analyzing water quality data are:

1) Water quality data with similar means and similar standard deviations. The difference in the means is not appreciable and the standard deviation of the distributions are similar (no effect from BMP on parameter).

2) Water quality data where the means either have a positive or negative difference and the inflow and outflow distributions overlap at concentrations well below the mean. This shows clear positive or negative removal at the mean but little difference in lower quantiles.

3) Water quality data where the means either have a positive or negative difference and the inflow and outflow distributions overlap at concentrations well above the mean. This shows clear positive or negative removal at the mean but little difference in higher quantiles.

7.4.5.4 Overview of Results of Efficiency and Effluent Quality by BMP Type and Parameter

To summarize the general performance of each BMP type, factsheets have been developed for the BMP Database that are presented as a compilation of effluent concentration statistics and box plots organized by water quality parameter. These plots allow for a quick overview of the range of influent and effluent concentrations across a number of structural BMPs of similar type. Narrative interpretations of the statistical summaries are also included in each fact sheet.

The summaries of each BMP and parameter focus on two separate data analyses:

1) A data set composed of each BMP study's average EMCs over the entire respective monitoring period, grouped by BMP category.

2) A data set comprised of all of the individual effluent EMCs, grouped by BMP category.

For each water quality constituent examined, only those BMP studies reporting at least three influent and effluent EMCs were included in either data set. While this minimum threshold permits the actual calculation of the reported statistics (e.g., mean, median, percentiles), the robustness of such statistics is limited for these smallest samples.

The first data set (averaged EMCs) "weighs" the water quality data for each individual BMP study equally (one average EMC value per BMP study) no matter the number of events monitored, thereby placing the emphasis of the evaluation on whether similar types of BMPs at a variety of different sites achieve comparable average effluent quality. This analysis mutes the influence of individual events, and does not favor BMP studies that report a relatively large number of EMCs. The second analysis compares the distribution of effluent water quality from individual events by BMP category, thereby providing greater weight to those BMPs for which there are a larger number of EMCs reported. This represents an important distinction between the two analyses, and it is essential that interpretation of the performance summaries reflect how the data has been compiled and presented.

Notched box plots are used to graphically display the categorized distributions from both data sets. The notches encompass the 95 percent confidence interval of the median (averaged EMCs or individual EMCs, depending on the analysis) and provide a graphical, nonparametric means of assessing the difference between the central tendencies of multiple distributions. A logarithmic scale was determined to be best suited for plotting the data. The log-scale box plots were created utilizing the following method to calculate the upper and lower confidence levels:

1) The natural logs of the effluent values (averaged EMCs or individual EMCs, depending on the analysis) for a given BMP category are sorted in ascending order.

2) The upper and lower quartiles (i.e., the 75th and 25th percentiles) are calculated, following Tukey (1977).

3) The confidence interval of the median is calculated based on the upper and lower quantiles, following McGill et, al, (1978).

4) The median and confidence interval is translated back to arithmetic space. These values are used to delineate the upper and lower bounds of the notch on the box plots.

For both the distributions of averaged EMCs by BMP category and the distributions of individual EMCs by BMP category, the arithmetic values of the median and associated upper confidence level (UCL) and lower confidence level (LCL) are provided in the table that accompanies each summary.

An assessment was also made of the difference between the median effluent values and the corresponding influent values for both data sets. This assessment is critical because it provides a measure of whether or not the data indicate a statistically significant difference in pollutant levels between the influent and effluent. To perform this test, the median, UCL, and LCL for influent values were calculated in the same manner as for the effluent. A significant difference between the median influent and effluent values is assumed if their respective confidence intervals do not overlap; otherwise, the difference is not considered statistically significant. The same test may be performed graphically by plotting influent and effluent notched box plots side-by-side and comparing the confidence limits visually.

In many instances, no significant difference between influent and effluent medians was determined. Therefore, it is not possible to determine with any certainty whether the BMP had an effect or simply that the characteristics of the runoff treated (for example, low influent concentrations) govern the distribution of effluent values. Where the analysis of significant difference indicates that effluent levels are *greater* than influent, this is noted in the text and as a footnote to the tabulated values.

A brief synopsis describing the parameter in question and the mean effluent concentration for each BMP is given in the summary page. An example of a BMP parameter summary sheet is given in Exhibit 7-18.

Note that there are several limitations to these generalized BMP performance summaries due to the grouping of data from several studies.

1) The studies grouped into the various BMP categories may have widely varying designs that have direct influence on their performance.

2) A large effort has been made to assure the quality of the data; however some studies may have been miscategorized.

3) Local hydrology and drainage area conditions may have a large influence on the performance of BMPs.

4) There are an unequal number of data points within and among each study and BMP category. This may bias the statistical summary results.

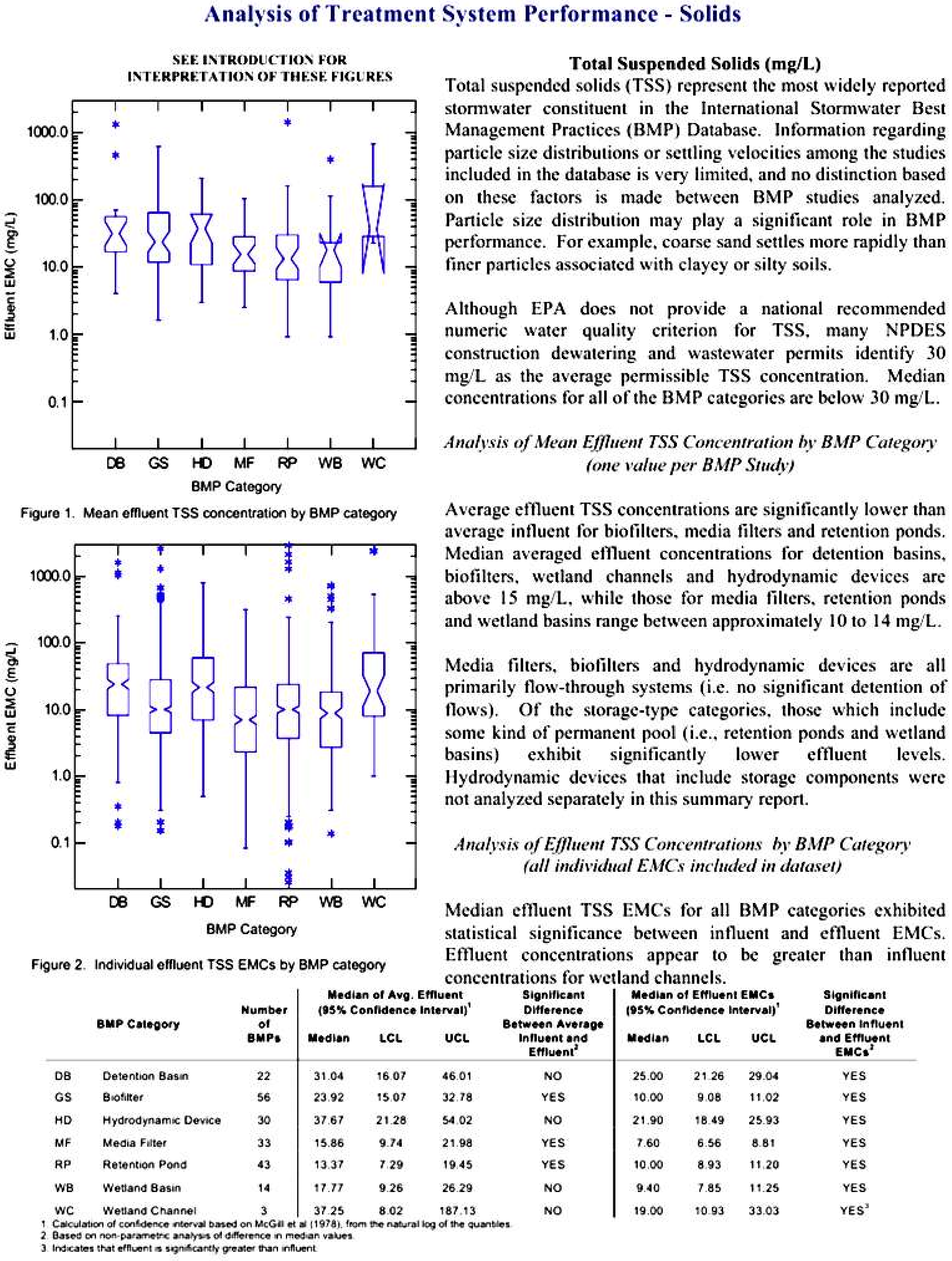
While the BMP performance fact sheets are a major step toward quantifying the general performance of BMPs in the Database, it is recognized that there is more research to be done and more data to collect in order to increase the confidence in the statistical summaries. In the future, there may be enough data to separate individual studies based on a variety of factors that are suspected to influence performance.

7.5 Conclusions

The analysis of Best Management Practices (BMPs) performance data is often complex and challenging. Consistency in performance analysis is needed to efficiently facilitate the use of individual study results as well as make broader conclusions with regard to the performance of larger classes of BMPs. Performance analysis methods must account for changes in concentration, pollutant load, and volume of discharge that result from the BMP. Methods must also account for measurements below detection limit, small samples size, availability of paired or unpaired datasets, and unknown statistical distributions. While a variety of analysis methods can yield meaningful results provided that appropriate practices are followed, the effluent probability method is recommended because of its flexibility and reliability in describing the fundamental aspects of BMP performance. Data from the BMP Database can be visualized and compared via scatter plots, box plots and probability plots in order to reach conclusions about the absolute and relative performance of BMPs.

This guidance document only briefly describes some of statistical methods available to the data analyst and is not intended to be a standalone statistical reference. Users are encouraged to seek additional information on how to apply the methods described in this manual and their limitations from the vast body of statistical literature and available statistical software.

Exhibit 7-18. Example of BMP Parameter Summary Sheet



Analysis of Treatment System Performance - Solids

SEE INTRODUCTION FOR
INTERPRETATION OF THESE FIGURES

Figure 1. Mean effluent TSS concentration by BMP category

Figure 2. Individual effluent TSS EMCs by BMP category

Total Suspended Solids (mg/L)

Total suspended solids (TSS) represent the most widely reported stormwater constituent in the International Stormwater Best Management Practices (BMP) Database. Information regarding particle size distributions or settling velocities among the studies included in the database is very limited, and no distinction based on these factors is made between BMP studies analyzed. Particle size distribution may play a significant role in BMP performance. For example, coarse sand settles more rapidly than finer particles associated with clayey or silty soils.

Although EPA does not provide a national recommended numeric water quality criterion for TSS, many NPDES construction dewatering and wastewater permits identify 30 mg/L as the average permissible TSS concentration. Median concentrations for all of the BMP categories are below 30 mg/L.

Analysis of Mean Effluent TSS Concentration by BMP Category
(one value per BMP Study)

Average effluent TSS concentrations are significantly lower than average influent for biofilters, media filters and retention ponds. Median averaged effluent concentrations for detention basins, biofilters, wetland channels and hydrodynamic devices are above 15 mg/L, while those for media filters, retention ponds and wetland basins range between approximately 10 to 14 mg/L.

Media filters, biofilters and hydrodynamic devices are all primarily flow-through systems (i.e. no significant detention of flows). Of the storage-type categories, those which include some kind of permanent pool (i.e., retention ponds and wetland basins) exhibit significantly lower effluent levels. Hydrodynamic devices that include storage components were not analyzed separately in this summary report.

Analysis of Effluent TSS Concentrations by BMP Category
(all individual EMCs included in dataset)

Median effluent TSS EMCs for all BMP categories exhibited statistical significance between influent and effluent EMCs. Effluent concentrations appear to be greater than influent concentrations for wetland channels.

	BMP Category	Number of BMPs	Median of Avg. Effluent (95% Confidence Interval)[1]			Significant Difference Between Average Influent and Effluent[2]	Median of Effluent EMCs (95% Confidence Interval)[1]			Significant Difference Between Influent and Effluent EMCs[2]
			Median	LCL	UCL		Median	LCL	UCL	
DB	Detention Basin	22	31.04	16.07	46.01	NO	25.00	21.26	29.04	YES
GS	Biofilter	56	23.92	15.07	32.78	YES	10.00	9.08	11.02	YES
HD	Hydrodynamic Device	30	37.67	21.28	54.02	NO	21.90	18.49	25.93	YES
MF	Media Filter	33	15.86	9.74	21.98	YES	7.60	6.56	8.81	YES
RP	Retention Pond	43	13.37	7.29	19.45	YES	10.00	8.93	11.20	YES
WB	Wetland Basin	14	17.77	9.26	26.29	NO	9.40	7.85	11.25	YES
WC	Wetland Channel	3	37.25	8.02	187.13	NO	19.00	10.93	33.03	YES[3]

1. Calculation of confidence interval based on McGill et al (1978), from the natural log of the quantiles.
2. Based on non-parametric analysis of difference in median values.
3. Indicates that effluent is significantly greater than influent.

7.6 References

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Chapter 8
LOW IMPACT DEVELOPMENT MONITORING

Low Impact Development (LID) is a stormwater management strategy that can be used to reduce runoff and pollutant loadings by managing runoff close to its source. The purpose of the LID monitoring guidance in this Manual is two-fold:

1) to provide monitoring guidance to evaluate hydrologic and water quality related performance of LID sites; and
2) to develop an initial standard protocol that compares the performance of LID studies to each other and to traditional stormwater Best Management Practice (BMP) monitoring studies.

The topics addressed in this chapter include an introduction to basic LID concepts, strategies for monitoring LID sites, and guidance on how to collect and report data. Information about how to interpret and evaluate LID monitoring data is included in Chapter 9. Selected LID monitoring case studies are included in Chapter 10.

Note: The term "green infrastructure" is commonly used to describe LID practices that are used in urban environments. For the purpose of this manual, the terms "green infrastructure" and "LID" are used interchangeably.

8.1 Introduction to LID

8.1.1 Basic LID Concepts

LID is an approach to stormwater management that seeks to minimize the potential adverse physical and chemical impacts of urban runoff by managing runoff close to its source. The Low Impact Development Center provides this description of LID:

> LID is an innovative stormwater management approach with a basic principle that is modeled after nature: manage rainfall at the source using uniformly distributed decentralized micro-scale controls. LID's goal is to mimic a site's predevelopment hydrology by using design techniques that infiltrate, filter, store, evaporate, and detain runoff close to its source. Techniques are based on the premise that stormwater management should not be seen as stormwater disposal. Instead of conveying and managing/treating stormwater in large, costly end-of-pipe facilities located at the bottom of drainage areas, LID addresses stormwater through small, cost-effective landscape features located at the lot level. These landscape features, known as Integrated Management Practices (IMPs), are the building blocks of LID. Almost all components of the urban environment have the potential to serve as an IMP. This includes not only open space, but also rooftops, streetscapes, parking lots, sidewalks, and

medians. LID is a versatile approach that can be applied equally well to new development, urban retrofits, and redevelopment revitalization projects (http://www.lid-stormwater.net).

Exhibit 8-1. Other Resources for More Information on LID

U.S. Environmental Protection Agency Low Impact Development Web Page: http://www.epa.gov/owow/nps/lid/

Low Impact Development Center: http://www.lowimpactdevelopment.org/

University of New Hampshire Stormwater Center: http://www.unh.edu/erg/cstev/

National LID Clearinghouse: http://www.lid-stormwater.net/clearinghouse/index.html

North Carolina State University/North Carolina Cooperative Extension Stormwater Engineering Group: http://www.bae.ncsu.edu/stormwater/

Puget Sound Partnership Resource Center: http://www.psparchives.com/our_work/stormwater/lid.htm

Villanova Urban Stormwater Partnership: http://www.villanova.edu/vusp/

Prince George's County, Maryland: http://www.goprincegeorgescounty.com/government/agencyindex/der/lid/bioretention.asp

Jordan Cove Urban Watershed Project: http://www.jordancove.uconn.edu/jordan_cove/about.html

Street Edge Alternatives (SEA Streets) Project: http://www.seattle.gov/UTIL/About_SPU/Drainage_&_Sewer_System/Natural_Drainage_Systems/Street_Edge_Alternatives/index.asp

National Academy of Sciences, National Research Council Report: *Urban Stormwater Management in the United States*: http://www.nationalacademies.org/morenews/20081015.html

Exhibit 8-1 provides an overview of key websites that can be referenced for more information on LID concepts, design guidance, existing studies, and ongoing research.

While many of the individual LID techniques are comparable to some types of traditional stormwater BMPs, LID is an overall design philosophy based on the implementation of multiple, distributed small-scale controls throughout a development site. Exhibit 8-2 compares some LID practices to traditional stormwater BMPs. Guidance provided in Chapters 2 through 7 of this manual can generally be followed when monitoring individual LID BMPs. However, effectively monitoring overall LID sites can offer a unique challenge and is the focus of this chapter. To more clearly illustrate the differences between monitoring individual practices and monitoring at the site level, the following specific descriptions are provided:

1) Individual LID Practice Monitoring: In this case, an individual LID practice (e.g., a bioretention cell, a biofilter, infiltration basin, or permeable pavement parking lot) is isolated to monitor performance. This may also include monitoring a combination of practices in series such as a biofilter preceding a bioretention cell in a parking lot. These types of monitoring programs can generally follow the guidance previously provided in Chapters 2 through 7 of this manual, with particular attention to designing studies in a manner that incorporates a robust

hydrologic monitoring component and properly addresses the challenges that come with monitoring small watersheds with often poorly defined inflow and outflow monitoring stations. A number of studies exist that demonstrate individual LID practice monitoring approaches (e.g., Hunt et al. 2008, Davis 2008, Emerson and Traver 2008, Barrett et al. 2006, Roseen et al. 2006 and 2009, Li et al. 2009).

2) Overall Site Level LID Monitoring: In this case, the composite site level performance, which includes multiple distributed controls, is monitored. An example of a monitoring study of this type is the approximately 12-acre Somerset Development in Maryland (Cheng et al. 2003). Due to the varying types, number, and spatial distribution of the LID practices, and more importantly the lack of specific discharge locations, these types of monitoring study designs can present significant challenges to the researcher. In some cases, modifications to the drainage system must be made, either in the design phase or as a post-construction retrofit, to facilitate effective monitoring. Historically, reference or "parallel" watershed study designs have often been used to assess performance at the site level. Alternatively, "before and after" studies can provide very useful insight into how well a LID site is performing relative to pre-development hydrology, which is the fundamental stated goal for LID development and retrofit projects.

3) Hybrid LID-Traditional Site Level Monitoring: In this case, a site to be monitored may include multiple distributed controls and LID principles, but it may also incorporate some traditional larger-scale stormwater management components at the downstream end of the study site, particularly for flood control. For example, a study by Selbig and Bannerman (2008) involves a Cross Plains, Wisconsin LID site with multiple distributed controls and a larger-scale infiltration basin located at the downstream end of the drainage. Retrofits of existing subdivisions would often fall into this category. Historic approaches to monitoring these types of sites are similar to those for the overall LID-based site development described above. These types of sites may be more straightforward to monitor relative to the overall LID-based sites because there is often a centralized discharge point to facilitate sample collection.

Exhibit 8-2. Relationship between LID and Traditional Stormwater BMP Terminology

LID Practice	**Traditional Stormwater Practices** *(included in 1999 Release of BMP Database)*
Bioswale	Grass Filter Strip and Swale
Bioretention Cell[1]/Rain Garden	Vegetated Media Filter/Vegetated Infiltration Basin
Infiltration Basin	Infiltration Basin
Infiltration Trench, Seepage Pit	Percolation Trench and Dry Well

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[1] Bioretention is used to refer to systems with and without underdrains. Systems with underdrains discharge predominantly to the downstream stormwater conveyance system, but may promote incidental volume reduction through infiltration below underdrains and soil soaking and drying. Systems without underdrains discharge primarily to groundwater or evapotranspiration, not to the downstream conveyance system. These systems may fill up and bypass, but have no other surface discharges.

LID Practice	**Traditional Stormwater Practices** *(included in 1999 Release of BMP Database)*
Wet swale	Wetland Channel and Swale
Stormwater Wetland Pocket Wetland	Wetland Basin
Porous Pavement (multiple types)	Porous Pavement (multiple types)
Tree Planter Downspout Planter Box	Vegetated Media Filter
Green Roof	
Rain Barrel/Cistern	Detention/Retention (Tank)
Manufactured Devices (not typically classified as LID, but can provide pre-treatment as part of an LID treatment train)	Manufactured Device: media filtration units
	Other Manufactured Devices: oil/grease separator, hydrodynamic separator, swirl concentrator
Non-structural Practices (e.g., education, source controls)	Non-structural Practices (e.g., education, source controls)
Site Design Practices (e.g., narrow streets, reduced imperviousness, minimal curb and gutter, open drainage, preserving natural areas)	Some Site Design Concept (e.g., “Minimizing Directly Connected Impervious Area,” “Disconnecting Hydraulically Connected Impervious Area”)

8.1.2 What Distinguishes a LID Site?

LID sites can be characterized based on overall approach to site design and typical design features, with several common features described below.

Site Planning

Site planning is a key element of the LID sites and is often what fundamentally distinguishes new LID developments from their traditional counterparts. Site planning for LID sites will typically include one or more of the following elements:

- Conservation and Minimizing Disturbance: Preserve natural infiltrative characteristics of the soils by minimizing disturbance and avoiding compaction throughout project phasing and construction sequences.

- Minimizing Building and Travelway Coverage: When constructing buildings on site, minimize impervious rooftops and building footprints. For travelways, this includes constructing streets, driveways, sidewalks, and parking lot aisles to the minimum widths necessary, provided that fire protection access, adequate parking, public safety and a walkable environment for pedestrians are not compromised.

- Maintaining Natural Drainage Patterns and Designing Drainage Paths to Increase Time of Concentration: Key elements include: maintaining depressions and natural swales; emphasizing sheet flow instead of concentrated flow; increasing the number and lengths of flow paths; maximizing non-hardened drainage conveyances; and maximizing vegetation in areas that generate and convey runoff. This group of practices often includes eliminating curbs and gutters or including curb cuts to allow runoff to enter LID practices, such as roadside swales, bioretention areas, or infiltration trenches.

- Source Controls: These practices include: minimizing pollutants; isolating pollutants from contact with rainfall or runoff by segregating, covering, containing, and/or enclosing pollutant-generating materials, wastes, and activities; and conserving water to reduce non-stormwater discharges.

- Specific LID Techniques: Common techniques used at LID sites include permeable pavements, natural drainage system elements, stormwater harvesting, and green roofs. (These are discussed separately below.)

For example, a LID site may be a several acre mixed urban community that includes high density cluster development with green roofs on multifamily homes, downspout planter boxes or rain gardens in commercial landscaped areas, permeable pavement on driveways and sidewalks, and residential roads having no curbs or gutters with vegetated swales.

Given the distributed nature of these controls and practices, LID monitoring approaches must be carefully developed in order to provide meaningful data within a reasonable budget. In many cases it is not realistic to monitor the performance of each individual practice. This is one of the key reasons that overall LID site monitoring often compares LID site hydrology and water quality to that of one or more reference watersheds. Exhibit 8-3 shows a side-by-side comparison of a traditional development and an LID-based development. As can be seen in the exhibit, the LID site is fundamentally different from a planning perspective and incorporates conservation of open space and preservation of native vegetation, and minimizes the disturbed area of the development.

Exhibit 8-3. Traditional versus LID Development Comparison (PSAT, 2005)

The LID site shown in Exhibit 8-3 also illustrates the integration of traditional BMPs in an overall LID scheme. A vegetated pond is provided near the outlet of the catchment, complementing LID site design principles and on-site stormwater controls by capturing and treating water that cannot be captured and eliminated at the lot level.

Typical Design Features

Inherently the design of low impact developments and retrofit projects is a creative process and is quite site specific; however, a number of typical features are consistently incorporated into many designs including:

- Natural Drainage System Elements/Vegetated Infiltration/Filtration Features: Infiltration practices are used to directly route runoff to the subsurface where it is temporarily held in pore spaces before evaporating from surface soils, transpiring from vegetation, percolating down to the groundwater table, or discharging via interflow. One way to do this is through bioretention cells or rain gardens that are designed to capture sheet flow and hold it in the pores of amended soil and shallow surface storage before the captured water percolates to groundwater or evapotranspirates. These systems provide significant protection of groundwater quality by facilitating contact with amended soils before percolation to groundwater. Vegetated practices can also be used; these focus more on evapotranspiration processes by incorporating absorptive soils (e.g., peat) and dense vegetation. Vegetation can also keep the top layer of soil stable and open for infiltration. Bioswales and vegetated filter strips can also treat stormwater in a similar way, but they do not typically have appreciable surface storage and often receive runoff along their entire length. Another way is through planter boxes which are structural units that intercept runoff along a curb or from a roof downspout. While these devices can be easier to implement in ultra-urban retrofit situations and effectively delay the hydrograph response, the volume reductions may not be significant if the device includes an underdrain connected to the storm drain system.

- Green Roofs and Green Facades: Green roofs and green facades are increasingly common. These design features contain a specially engineered, light-weight media that supports vegetative growth—typically short, drought- and temperature-resistant grasses in a variety of forms. The green roof media and vegetation have the potential to store and evapotranspire precipitation, as well as reduce peak flows through temporary storage. Green roofs and facades have many additional benefits including significant reductions in urban heat island effects.

- Cisterns/Rain Barrels/Rainwater Harvesting: These features can be used to alter runoff timing and reduce peak flows and decrease runoff volumes where reuse is effectively incorporated into the design. Typically, runoff from traditional roofs can be diverted and collected in rain barrels or cisterns, where legally permissible. (In some parts of the country, water rights constraints limit this practice.) This practice reduces runoff volume while storing water for future non-potable uses such as irrigation. When using this technique, barrels should be screened to intercept debris and control mosquitoes, or the water should be directed to an infiltration basin or rain garden to recharge groundwater.

- Permeable Pavements, Pavers, and Permeable Overlays: Parking lots and roadways contribute a significant portion of the runoff from a typical development area. Pervious pavements and paver systems are designed to allow stormwater to percolate or infiltrate through the surface into the soil below or to filter runoff through a subsurface media thereby reducing runoff volumes, decreasing peak flow rates, and improving water quality.

8.1.3 LID Monitoring Philosophy

LID monitoring is currently (late 2009) in its infancy and continues to evolve as LID practices and site designs are implemented in more communities. The majority of the currently completed or published LID studies focus on monitoring individual LID practices, such as a single bioretention cell or a single green roof on a building to identify and understand the mechanisms governing treatment and to assess performance of the individual practice. Although the specifics of monitoring individual LID practices can present significant challenges, the means and methods are fundamentally similar to approaches for monitoring more conventional systems.

Fundamentally, the overall goal of incorporating LID into developments is to affect the ways in which overall site design and implementation impact hydrology and water quality. It is this level of monitoring for which there is not currently adequate guidance. It is the intent of this chapter to focus on this site level monitoring and to suggest approaches to assess the collective effects at this scale. A number of researchers have realized the critical importance of assessing the performance of LID sites at this scale. Several studies of this nature are listed in Exhibit 8-4 and discussed further in Chapter 10.

As a general starting point, LID monitoring at the site level typically follows a reference watershed approach (Clausen and Spooner 1993) where one or more of the watersheds acts as a control (undeveloped or conventional treatment watershed) for which a baseline for comparison is formed, and the other watershed represents the treatment (LID treatment watershed) to be analyzed. (Use of the reference watershed approach is discussed in more detail below in Section 8.2.2.) “Nested” monitoring may also be conducted where individual LID practices within the catchment are monitored in addition to the overall watershed whereby providing a means to differentiate normal watershed processes and the effects of individual LID practices. Because of these multiple layers of potential complexity and high number of watershed variables involved in this type of monitoring, it is particularly critical that substantial forethought and planning be completed to clearly identify the objectives of the monitoring project.

In addition to reference watershed studies, “before and after” studies have a great deal of merit for LID site level monitoring as they provide experimental control for a host of variables in the study design. Depending on the goals of the monitoring project, detailed analysis of high frequency and accurate intra-storm data in “before and after” studies may be critical for obtaining information needed to evaluate the likely long-term performance of LID sites.

The seven planning steps described in Chapter 2 should be followed along with the additional guidance presented in this chapter in order to set realistic monitoring program goals and execute the program in an efficient and cost effective manner. In shaping a monitoring program, it is helpful to be aware of some of the common challenges associated with monitoring LID at the overall development scale.

Exhibit 8-4. Past and/or Current Catchment Scale LID Monitoring Studies

Study Location	Study Overview	Source
Jordan Cove, CT	One control and two treatment watersheds (conventional and LID). Low density single family residential. Evaluated construction-phase and post-construction runoff water quantity and quality.	University of Connecticut. http://www.cag.uconn.edu/nrme/jordancove/
Cross Plains, WI	Before/After, Control/Impact study. Treatment watershed included LID practices on-site and detention and infiltration basin at outlet. Monitored several years of runoff water quantity and quality.	Selbig and Bannerman 2008. http://pubs.usgs.gov/sir/2008/5008/
Somerset, MD	One control and one treatment watershed. Limited LID in treatment watershed. Monitored in parallel for two years at time of publication. Monitored flowrate and water quality	Cheng et al. 2003. http://www.scdhec.gov/environment/water/lid/pdf/somerset.pdf
Burnsville, MN	One control and one treatment watershed. Monitored in parallel without retrofit for calibration period, then retrofit treatment watershed with bioretention. Monitored flowrate and volume only.	Barr Engineering 2006. http://www.co.dakota.mn.us/EnvironmentRoads/EnvirProtect/Stormwater/LID.htm

8.1.4 Site Level LID Monitoring Challenges

Site level LID monitoring presents a number of different challenges above and beyond those already present in traditional BMP monitoring. Traditional stormwater designs typically direct flows to a central location that is designed to store and slowly release flows, often with defined inlets and outlets. This is not the case with many LID systems. The multitude of discharge locations and distributed nature of the controls often does not present an opportunity to select a single monitoring point sufficient to assess site hydrology and water quality. A variety of other challenging factors which may be present on an LID site are listed below.

1) The limits of the "site" may be difficult to define.
2) The extent of LID implementation at the site must be quantified in order to compare results to other sites.
3) Concentrated flow discharge locations may be hard to define or not present.
4) Watershed boundaries may change as a function of factors such as rainfall intensity, antecedent soil moisture conditions, season, winter conditions, and so on.
5) Run-on from uphill areas may commingling with flows from the site.
6) Events may produce no discharge or very low discharge during small events.
7) Soil moisture and antecedent conditions play a critical role in performance.
8) Surface and subsurface conditions across the site may have a high degree of spatial variability.
9) Groundwater/vadose zone monitoring may be necessary to evaluate the overall site water balance and evaluate groundwater contamination potential.
10) Evapotranspiration can be a critical performance factor and is understood to vary as a function of climate and weather.
11) Infiltration rates can be a critical performance factor and is understood to vary with temperature, including the effects of freezing on facility operation.
12) Vegetation characteristic exhibit seasonal variations.
13) Performance is understood to be highly dependent maintenance status.
14) It is often difficult to identify a reference watershed that shares common physical characteristics and is in close proximity. Inevitable differences between the reference and the test watersheds must be accounted for.
15) Greater quantities of data may be needed to achieve statistical significance considering the large number of variables influencing the performance of overall LID sites.

8.2 Monitoring Study Design for LID Projects

Monitoring design for LID projects shares many similarities with traditional monitoring projects. However, a few key differences exist. The most fundamental difference is that LID monitoring may occur at both the practice level and the site level. Exhibit 8-5 shows examples of possible LID monitoring locations in comparison to typical BMP monitoring locations. It also illustrates the concept of practice level and site level monitoring.

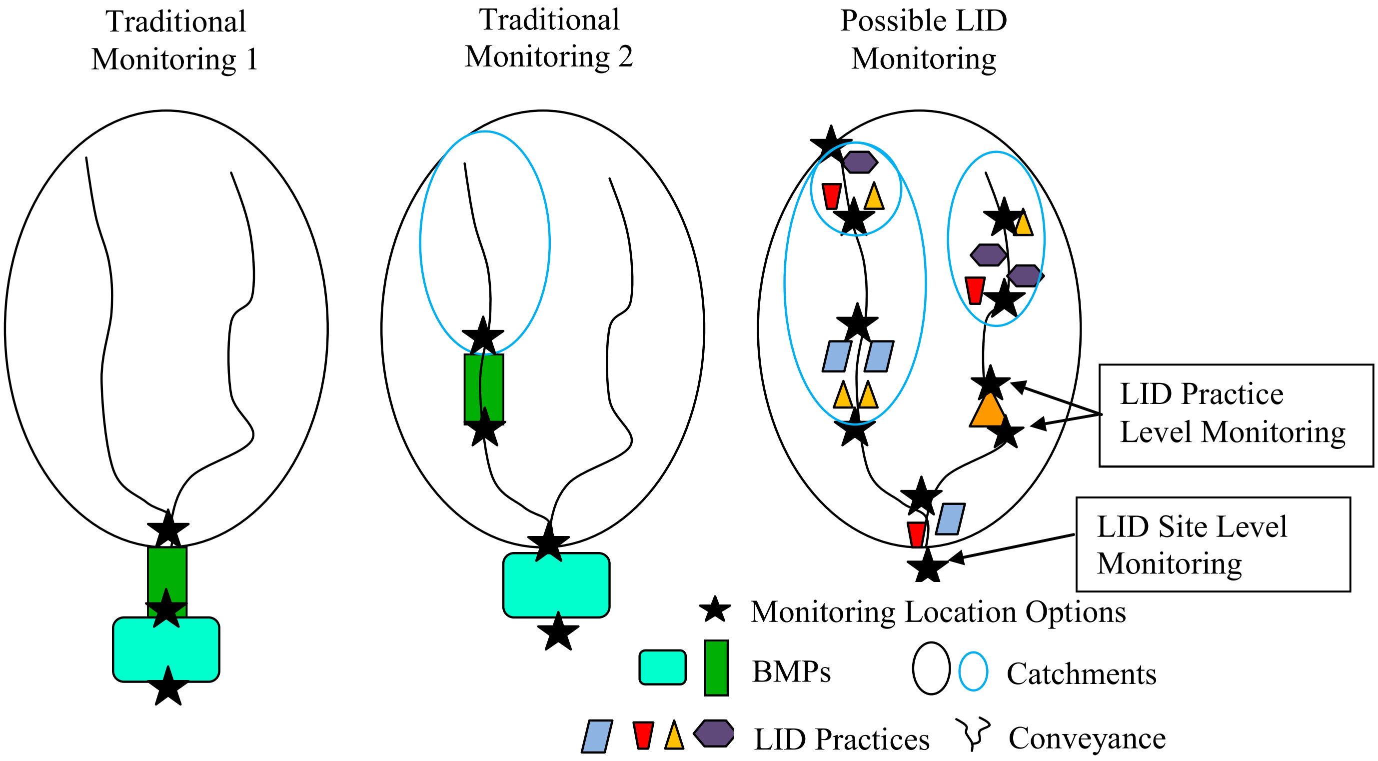


Exhibit 8-5. Examples of Traditional versus Possible LID Monitoring Project Design

This chapter extensively references elements of Chapters 1 through 7 as practice level monitoring is similar to traditional monitoring. The most significant difference between LID practice level monitoring and traditional monitoring is the nature of the practice. LID practices tend to be more focused on site hydrology as they are more dependent on natural processes such as infiltration and evapotranspiration. Because of this, study objectives may slightly differ from traditional studies.

Site level monitoring is different than traditional monitoring, primarily in its spatial scale and study objectives. Traditional monitoring has a readily-available baseline (i.e. the BMP influent) whereas the “influent” to an LID site cannot typically be monitored.

8.2.1 LID Monitoring Study Objectives

The study objectives listed in Chapter 2 are generally applicable or adaptable to LID studies, particularly to practice level studies. The following list is adapted for practice level and site level LID studies (Exhibit 8-6).

Exhibit 8-6. Typical Study Objectives for Practice and Site Level LID Monitoring Studies

Practice Level LID	Site Level LID
How does the hydrology for developed conditions compare with pre-development hydrology in terms of peak flow rates, runoff volume, peak timing, site infiltration capacity, site water balance, and so on?	
What degree of pollution control or effluent quality does the LID practice provide under normal conditions (i.e., representative storm types)?	To what extent does the LID site reduce the concentration of pollutants compared to a site without LID practices under normal conditions (i.e., representative storm types)?
How does this performance vary from pollutant to pollutant?	
How does this normal performance vary with large or small storm events?	
How does this normal performance vary with rainfall intensity?	
How do LID practice design variables affect performance?	How does the combination of LID practices present on a site and the design parameters of these practices affect performance of the site as a whole?
How does performance vary with different operational and/or maintenance approaches?	
Does performance improve, decay, or remain stable over time?	
Does performance vary seasonally? (For example, to what extent is infiltration capacity reduced during cold temperatures?)	
How does this LID practice's performance compare to the performance of other LID practices?	How does this LID site's performance compare to the performance of other LID sites?
How does this LID practice's performance compare to the performance of other types of BMPs?	How does this LID site's performance compare to the performance of other types of BMPs?
Does this LID practice help achieve compliance with water quality standards?	Does this combination of LID practices help achieve compliance with water quality standards?

Ultimately, the study design attempts to answer these questions by obtaining data that can be used to characterize (at least partially) the monitored system as well as interpreted or extrapolated to quantify (at least partially) one or more of the fundamental descriptions of system performance. Fundamental elements of system characterization include:

- The physical properties of the system as they relate to hydrologic response and water quality
- The conditions of the system at the time of monitoring
- The operation of the system

Fundamental descriptors of system performance include:

- The long-term water balance of the system
- Cumulative flow duration, flow frequency, volume frequency, and other statistical descriptions of aggregate hydrologic response
- Representative distributions of concentrations and frequency patterns of concentration
- Long-term average pollutant loadings and distribution of pollutant loading
- Trends in each of these descriptors by season, maintenance considerations (i.e. time since maintenance, frequency of maintenance), and/or age of system

It is impossible to completely characterize or describe performance of any system; however well-defined systems with limited monitoring points generally are more fully described than systems with less defined inflows and outflows like those found in LID systems. LID monitoring studies typically use surrogate metrics to attempt to partially characterize the system and partially describe performance. Chapters 1 through 7 describe the metrics that are recommended to characterize practice level studies and interpret results. This section describes the metrics that are recommended to be collected to characterize LID sites. Chapter 9 discusses the interpretation of results as they relate to fundamental descriptions of system performance.

8.2.2 Use of Reference Watersheds

When monitoring LID at the site level, performance can be assessed by comparing hydrologic and water quality characteristics from the LID site to one or more reference watershed conditions. Reference watersheds may include the following:

1) Before-After/Control-Impact (BACI): This monitoring strategy compares a LID site to a control site, using either or both of these approaches:

    a. The Before-After approach involves monitoring a proposed development site before development of the site using LID and comparing those conditions after development. The “before” time period can be referred to as the “calibration” period and must span enough time to obtain a reasonably characteristic hydrologic record of the site. After development using LID, a comparable hydrologic monitoring time period is needed to compare the "before and after" watershed response to storm events. Challenges associated with this type of monitoring strategy include the time and cost associated with monitoring to develop an adequate hydrologic record; Clausen (2007) has recommended a minimum of 5 to 10 years.

b. The Control-Impact approach involves selecting a control watershed in a nearby comparable undeveloped watershed and monitoring the "control" and the "impact" simultaneously. Rather than comparing conditions "in time," this approach compares hydrologic performance "in space." While this approach may require less time, it is essential that the control watershed has similar characteristics (e.g., steam order, average slope, canopy, soils, size, and location) to the "impact" watershed prior to LID implementation. Finding an identical watershed is not realistic, so it is important to carefully document differences between the control and impact watersheds and adjust conclusions accordingly.

2) Comparison of traditional and LID developments: In this monitoring strategy, two watersheds with comparable pre-development characteristics are developed with comparable land use; one site is developed using traditional development techniques while the other site is developed using LID techniques. The performance of the two sites can then be compared. When using this technique, it is important to monitor response to a variety of storms (both large and small) so that premature conclusions are not drawn regarding performance of either location.

3) Comparison of a LID retrofit watershed to pre-retrofit conditions: This monitoring strategy is a variation of the approach described above in number two where sites developed with LID techniques are compared to other traditional developments. While sites developed with LID techniques can be compared to other traditional developments as described, it may be most direct and beneficial to compare LID retrofits to pre-retrofit conditions. It is important to characterize the site as a retrofit in study documentation as the extent of LID practice implementation may be restricted relative to a new development implementation of LID.

4) Multiple Techniques: Using a combination of all three monitoring strategies described above is another monitoring approach that can be used in LID site level studies. This combination of strategies can lead to the most robust conclusions about the LID site performance as evidenced in the Cross Plains, WI case study described in Chapter 10. In that study, the LID site is compared to the pre-development hydrology at the site and a nearby traditional development.

It is proposed by the authors that collection of high resolution hydrologic data during a relatively small number of events with adequate variation in precipitation volume, intensity, and antecedent conditions may, in some cases, provide adequate information for accurately predicting long-term hydrologic performance of systems under pre-development, pre-retrofit and LID conditions. The key to this approach is to use continuous datasets to carefully calibrate and validate hydrologic models of the systems, and then to use longer regional datasets to estimate performance over the long term. It is anticipated that this approach would work quite well for watersheds with short times of concentration in the "before" condition of retrofit projects (e.g., rooftops, parking lots, roadways, other retrofit projects), and for more controlled LID implementations such as green roofs, cisterns, and planter boxes. The applicability of this approach for less defined systems such as disconnected imperviousness, bioretention cells, and so on would be dependent on the ability to measure the performance of these systems accurately and the ability of the selected model to adequately represent the important processes in these systems. This approach should be explored as the practice of monitoring LID sites evolves.

Ultimately, the type of monitoring study designed is based on study objectives and project constraints. For example, if the research objective is to determine how well post-development conditions match pre-development hydrology, then the BACI strategy may be adequate. If the research objective is to compare performance between a traditional and a LID site, then strategy number three described above might be the best choice. If multiple study objectives exist, then a combination of strategies as described in number four may be the best approach. It should be noted that regardless of the monitoring program goals, if the study is well conducted, the results should be useful for drawing conclusions relative to other studies as well as between controls or test sites in the study itself. Also, regardless of the monitoring strategy chosen, thorough documentation of site characteristics and hydrologic characteristics is essential for meaningful results. This documentation is described in the next two sections.

8.2.3 LID Watershed Characteristics

LID watershed characteristics are the physical features and properties of an area containing LID practices, including the practices themselves, that influence its overall hydrologic response to rainfall events. These characteristics are reported as catchment-scale metrics that can be used to help compare performance monitoring data collected at different LID sites. Exhibit 8-7 contains a list of watershed characteristics currently requested in the BMP Database for all studies. Some elements that are currently "nice to have" for conventional watersheds will be "required" for LID watersheds. Likewise, additional metrics are needed to adequately characterize LID watersheds while accounting for the broad variability between these watersheds. These metrics are described in Exhibits 8-9 through 8-12. Since LID is relatively new and research is still evolving, the suggested additional metrics are only considered a starting point for LID and will likely be refined and expanded in the near future. The sub-sections below discuss the watershed characterization concepts to keep in mind when designing a LID monitoring study and explain how they can be used to help differentiate the hydrologic response of various LID watersheds. Exhibit 8-8 lists the acceptable land use categorizations of the BMP database that have been collected in the past. Additional land use categories added at this time are shown in Exhibit 8-10.

Exhibit 8-7. Watershed Characteristics Requested in the Stormwater BMP Database

General Watershed Information	Road and Parking Lot Information
Land Uses (See Exhibit 8-7)	Total Paved Roadway Area
Watershed Description (narrative)	Total Length of Curb and Gutter on Paved Roads
Total Watershed Area	Total Unpaved Roadway Area
Total Length of Watershed	Total Length of Curb/Gutter on Unpaved Roads
Total Length of Grass-Lined Channels	% Paved Roads Draining to Grass Swales/Ditches
Total Disturbed Area	% Unpaved Roads Draining to Grass Swales/Ditches
% Irrigated Lawn and/or Agriculture	Type of Pavement on Roadways
% Total Impervious Area in Watershed	Total Paved Parking Lot Area
% of Total Impervious Area that is Hydraulically Connected	Total Length of Curb/Gutter on Paved Parking Lots
% of Watershed Served by Storm Sewers	Total Unpaved Parking Lot Area
Storm Sewer Design Return Period (years)	Total Length of Curb/Gutter on Unpaved Parking Lots
Average Watershed Slope	% Paved Parking Lot Draining to Grass Swales/Ditches
Average Runoff Coefficient	% Unpaved Parking Lot Draining to Grass Swales/Ditches
Hydrologic Soil Group	Type of Pavement in Parking Lots (% Porous Concrete, % Porous Asphalt, % Modular)
Soil Type	Characterize Highway Conditions (Average Daily Traffic, Number of Lanes, Deicing Method)
Type of Vegetation (narrative)	Narrative description of the type of vegetation present

Exhibit 8-8. Land Use Types in the BMP Database

Land Use Categories Accepted in the Stormwater BMP Database (reporting is based on % of each type)	
Multi-Family Residential	Open Space
High Density Residential	Forest
Medium Density Residential	Rangeland
Low Density Residential	Orchard
Light Industrial	Vegetable Farming
Heavy Industrial	Restaurants
Office Commercial	Automotive Services
Retail	Maintenance Station
Highway	Unknown
Park & Ride	

It is critical to recognize that in site level LID studies the watershed *is* the BMP rather than an external factor to be documented as is the case in a conventional BMP study. In the case of site level "nested studies" (see Section 8.1.3), additional complexities arise because an individual LID practice, which would be considered a BMP in a practice level study, would now be considered just one element of an overall watershed characterization in the site-level study. These studies are complementary; however, as the detailed results from the practice level study can be used to help estimate bulk watershed characteristics at similar facilities throughout the watershed.

8.2.3.1 Watershed Geometry

The general geometry of a study watershed (e.g., total area, slope, overland flow width) is basic information that should be documented as part of any comprehensive LID site monitoring study. These parameters are easy to obtain and provide insight into the typical response that can be expected during a storm event. For example, small and steep watersheds are characterized by intense, short responses in the hydrograph, fast surface flow velocities, and low rates of infiltration. Conversely, watersheds generally described as having shallow slopes will respond more slowly to similar storm events and will yield lower peak discharges during those events. When all other factors are held constant, a flatter watershed will facilitate more infiltration and have higher rates of evapotranspiration. LID practices that depend on infiltration are generally best suited to treat smaller, less intense storm events that occur in mildly sloping watersheds. While this may be the case at present, innovative designs are continually being developed to test the bounds of applicability of LID techniques. Slope and overland flow patterns are easily obtained and should be documented as part of any comprehensive LID site study. Exhibit 8-9 shows watershed geometry information that is currently requested for practice level studies as well as the additional information requested for LID sites.

Exhibit 8-9. Existing and Recommended Watershed Geometry Parameters

Currently Requested Information	Relevance to LID Watershed Studies
Total Watershed Area	This is a fundamental watershed characteristic; it expresses potential for spatial variability in hydrologic characteristics (e.g., rainfall, soil properties).
Watershed Description (narrative)	This provides the context and initial screening of comparability to other studies.
Total Length of Watershed	This helps to estimate watershed lag; it expresses potential for spatial variability in hydrologic characteristics (e.g., rainfall, soil properties). It is too coarse to describe differences between conventional and LID site design (see Overland Flow Width).
Average Watershed Slope	This helps to estimate watershed lag, but it is not as important as defining the average slope of overland flow paths in developed areas (see Slope of Overland Flow Path).
Additional Information for LID Watershed Characterization	**Rationale**
Average Overland Flow Length	This is different from the total watershed length. It describes the area-weighted average drainage path length to an inlet or hardened conveyance.
Maximum Overland Flow Length	This is different from the total watershed length. It describes the maximum drainage path length to an inlet or hardened conveyance.
Narrative of Flow Patterns	This allows the user to describe watershed geometry-based LID practices that modify the flow patterns of the site in order to increase time of concentration and promote losses. The potential metrics that may be used to describe flow patterns include, but are not limited to, the following: • Time of concentration to a hardened conveyance; accompanied by method used to compute Tc and inputs • Hydraulic width per Stormwater Management Model (SWMM) documentation • Average lot depth • Average slope of pervious area

8.2.3.2 Vegetative Cover and Land Uses

Vegetative cover and the land uses in a study area are two major factors influencing the quality and quantity of runoff and should also be documented as part of a comprehensive LID monitoring study. The land use categories contained in the BMP Database are shown in Exhibit 8-8. Vegetation in a catchment, for example, stabilizes soils to prevent erosion, facilitates infiltration, and influences the site water balance through evapotranspiration. Vegetation is also a key component of many LID practices, such as green roofs, bioretention cells, and revegetation. The location of the vegetation on a LID site as well as the type, density, height of vegetation should be documented. In addition, the percent canopy coverage should be described for the individual LID practices as well as for the overall site. Documenting these types of characteristics is important because the vegetation at a LID site changes over time. Even after a LID site has been fully developed, these vegetation-related characteristics may require several years to fully mature, thereby delaying their beneficial effects.

The land use area breakdown is another fundamental descriptive component of any new development or redevelopment project. This information can be useful to describe how LID practices are implemented and distributed within a study watershed. For example, a LID site may include cisterns on 50 percent of the single family homes or bioretention cells treating 20 percent of the residential roads. Documenting a land use area breakdown for a study site can help classify the extent of LID implementation and can be used for future comparisons of LID site performance. Because land use trends are always changing, it is valuable to document the nature of imperviousness of the individual land uses in a watershed. Coupled with the information above, this information permits quantification of the amount of impervious area controlled by LID practices.

The preservation of natural soils, forests, and hydrologic features such as wetlands is a central LID principle. These natural areas provide a means to disperse, infiltrate, store, and evapotranspire stormwater runoff. Any preservation of natural land use or changes of the land use characteristics at a LID site should be documented. Exhibit 8-10 shows land use and vegetation information that is currently requested for practice level studies as well as the additional information requested for LID sites.

Exhibit 8-10. Existing and Recommended Land Use and Vegetation Parameters

Currently Requested Information	Relevance to LID Watershed Studies
Land use breakdown as percentage of total watershed	This describes the type of development and may be used as a surrogate for flow patterns, imperviousness, and expected water quality.
Watershed Description (narrative)	This provides the context of the study and allows an initial screening for comparability to other studies.
Total Disturbed Area	This describes the extent of site potentially producing greater runoff as a result of incidental compaction of pervious areas.

% Irrigated Lawn and/or Agriculture	This describes the extent of site potentially producing dry weather flows or having soil moisture content above seasonal normal for unirrigated land.
Type of Vegetation (narrative)	This permits the estimate of canopy cover and fraction of reference evapotranspiration (ETo).
Total Paved Roadway Area	This describes a major source of impervious area, which may be lumped with land use totals.
Total Unpaved Roadway Area	This describes a potential source of elevated runoff quantity that may not be characterized as impervious area.
Total Paved Parking Lot Area	This describes a major source of impervious area that may be lumped with land use totals.
Total Unpaved Parking Lot Area	This describes a potential source of elevated runoff quantity that may not be characterized as impervious area.
Characterize Highway Conditions (Average Daily Traffic, Number of Lanes, Deicing Method)	This is an indicator of expected runoff water quality.
Additional Information Recommended for LID Watershed Characterization	**Rationale**
Additional land use categories: • Open Space – Undisturbed • Open Space – Other (Describe) • Disturbed/Construction • Other (Describe)	This provides information for estimating hydrologic response and runoff water quality, and facilitates the interpretation of results. The quantity of undisturbed open space provides a measure of extent of LID implementation (preservation of open space is a central principle of LID).

8.2.3.3 Imperviousness and Connectivity

Following urbanization of a watershed, a significant hydrologic concern is the potential effect of increased imperviousness on receiving waters. In the absence of carefully planned hydrologic controls, the rate and volume of runoff may significantly increase, along with the associated pollutants and thermal loads. Because the basis of the LID design philosophy is to minimize the impact of development and to mimic the site's natural hydrology, it is important to document the types of design practices related to changes in imperviousness that are implemented at a LID site. For example, site design approaches such as splitting driveways, narrowing roads, and installing sidewalks on only one side of a street reduce the imperviousness of a development. Routing impervious areas (e.g., sidewalks, roads, roofs, and driveways) to adjacent pervious areas (e.g., lawns, landscaping, etc.) can reduce the "effective imperviousness" of the site. For example, runoff from roofs at a LID site can be directed into rain gardens instead of storm sewers, or curbs can be eliminated to allow road runoff to flow to bioswales. Likewise, parking lots can be drained to biofilters instead of road or sewer systems.

Streets and parking lots account for a large percentage of the total impervious area in a catchment. When impervious areas are directly connected to stormwater conveyance systems, they contribute large amounts of runoff compared to the runoff during natural conditions. Curbs and gutters that are traditionally used to concentrate and direct runoff to stormwater systems can be eliminated in a LID site and substituted with vegetated swales adjacent to roadways. Curbs can also be omitted in parking lots to allow runoff to flow into pervious area.

In addition to the total imperviousness of a study area, the directly connected impervious areas and the proportion of impervious surfaces with cover (ISWC) should also be estimated. Directly connected impervious areas (DCIA) are the impervious areas such as roofs and pavement that drain directly to the storm drain system without first draining to pervious areas or LID practices. ISWC is impervious area that is covered by vegetation (e.g., tree canopy) and, therefore, does not receive direct rainfall during some seasons of the year. Various methods to quantifying imperviousness data are discussed in Section 8.3.2.

Based on the above discussion, the useful impervious area metrics that should be estimated for a LID site when possible include: (1) total imperviousness along with estimates of the proportion of ISWC; (2) DCIA; and (3) the impervious area that flows to LID featrues. Additionally, any changes to impervious areas as a result of a LID retrofit should be recorded. For example, if 40 percent of an area was previously parking lots and 20 percent of the parking lot area was converted to a permeable pavement then the reduction in parking lot impervious area would be 20 percent and the overall reduction in impervious area would be 8 percent.

Is should be noted that the concept of disconnecting areas is not absolute. In a large enough storm or in sequential storms, the effectiveness of disconnection (e.g., routing downspouts over lawns, etc.) will typically be reduced, primarily due to decreased soil infiltration rates. For example, if a downspout was routed over a lawn that had been saturated by a previous storm, the expected volume reduction (i.e., degree of disconnection) would be less than if the lawn had been dry before the storm. Considerations of scale and relative volume are important and are discussed further in Section 8.2.3.5. The most recent version of the BMP Database allows data to be entered to help define a “degree of disconnection” rather than regarding disconnected impervious area as an “all or nothing” metric. Exhibit 8-11 shows the imperviousness and connectivity information that is currently requested for practice level studies as well as additional information that is requested for LID sites.

Exhibit 8-11. Existing and Recommended Imperviousness and Connectivity Parameters

Currently Requested Information	Relevance to LID Watershed Studies
% Total Impervious Area in Watershed	This is a fundamental watershed characteristic. It describes the percentage of the site where infiltration does not occur.
% of Total Impervious Area that is Hydraulically Connected (DCIA)	This provides a general description of the connectivity of watershed. It is the amount of area likely to discharge in a small storm event. Larger areas may behave as DCIA in larger events.
% of Watershed Served by Storm Sewers	This is an indicator of time of concentration of watershed, the overall connectivity, and the potential for conveyance losses.
Total Length of Grass-Lined Channels	This is an indicator of time of concentration of watershed, the overall connectivity, and the potential for conveyance losses.
Total Length of Curb and Gutter on Paved Roads	This is an indicator of time of concentration of roads, the connectivity of roads, and the potential for conveyance losses.
Total Length of Curb/Gutter on Unpaved Roads	
% Paved Roads Draining to Grass Swales/Ditches	
% Unpaved Roads Draining to Grass Swales/Ditches	
Total Length of Curb/Gutter on Paved Parking Lots	This is an indicator of time of concentration of parking lots, the connectivity of parking lots, and the potential for conveyance losses.
Total Length of Curb/Gutter on Unpaved Parking Lots	
% Paved Parking Lot Draining to Grass Swales/Ditches	
% Unpaved Parking Lot Draining to Grass Swales/Ditches	
Average Runoff Coefficient	This is the user estimate of runoff potential of watershed considering imperviousness and connectivity. Estimating this parameter without long term monitoring data requires professional judgment. It is typically the intent of LID site studies to quantify the average runoff coefficient.

Additional Information Recommended for LID Watershed Characterization	Rationale
Estimate of Average Imperviousness by Land Use	This allows a direct estimate of total watershed imperviousness and could support estimates of impervious area draining to LID practices if LID implementation is described by land use (e.g., bioretention in 40 percent of residential land use, etc.)
Estimate of Impervious Cover with Canopy (ISWC)	This provides information about the estimated hydrologic response and facilitates interpretation of results. It provides a measure of the extent of LID implementation (minimization of DCIA through vegetative cover is a fundamental principle of LID).

8.2.3.4 Soil Properties and Groundwater Conditions

Detailed soil and groundwater information is required to characterize the effectiveness of LID practices as these methods rely on infiltration and storage in natural soils and engineered media to operate efficiently. Knowledge of a site's soil characteristics can lead to making more economic construction choices that benefit the environment. For example, a building might be constructed on highly impermeable soils, while areas with high infiltration rates can be left undisturbed.

The stratigraphy of a site should be thoroughly assessed to locate any low/high permeability layers, sand/gravel layers, depth to groundwater, and any other factors that can help to determine subsurface flow patterns and the rate at which stored water would infiltrate in to the subsurface. Soil survey data available from the Natural Resources Conservation Service (NRCS) can be a useful resource for identifying site soil properties, and in some cases, depth to groundwater. That said, the NRCS surveys may be too coarse to confidently describe the detailed soil characteristics of a specific site. In addition, disturbance or relocation of soil during construction may reduce the representativeness of soil survey data in describing soil chemical and physical properties. Actual field samples from test pits should be collected when feasible to assess the grain size distribution, texture, organic content, nutrient levels, cation exchange capacity, or other characteristics. Additionally, in-situ infiltration test data can also be invaluable for both design and analysis of LID practices.

The installation of groundwater monitoring wells to obtain accurate and local seasonal high water table information is also very useful. This process can be expensive, however, and site-specific and regional considerations influence whether the cost is justified. For example, this type of monitoring would be important where a shallow aquifer may influence the performance of LID practices or in a community where the response of expansive clay soils to infiltration practices is being evaluated as part of the study. Where soil types and pollutant source areas suggest the potential for groundwater contamination from infiltration practices, groundwater and vadose zone discharge should be monitored to measure pollutant loading and removal in the soil column. Refer to Pitt et al. (1994) for information on evaluating risks of groundwater contamination and for guidance on monitoring for these effects. Exhibit 8-12 shows site soils information currently requested for practice level studies as well as additional information that is requested for LID sites.

Exhibit 8-12. Existing and Recommended Soil Parameters

Currently Requested Information	**Relevance to LID Watershed Studies**
Hydrologic Soil Group	This is an indicator of the magnitude of runoff from pervious areas. It may be different in developed conditions than what is reported in the soil survey due to soil compaction or mass grading/relocation.
Additional Information Recommended for LID Watershed Characterization	**Rationale**
Distribution of Hydrologic Soil Groups on Site (Fields for %A, %B, %C, %D)	This allows for a more robust description of larger sites, or sites with a range of compaction-related impacts.
Soil Conditions (narrative)	This allows the user to describe important aspects of the site soils. It may include: • Prevalent soil type (Unified Soil Classification) in developed areas at time of monitoring (not in the pre-development). • Measured saturated hydraulic conductivity in critical locations such as in the vicinity of infiltration-based practices. • Average and minimum depth to seasonally high groundwater in developed areas. • Degree of compaction and envelope of disturbance.

While it is recommended that soil should be sampled and analyzed to characterize site soil types and properties, the BMP database is not structured to handle soil datasets. Users will be able to provide narrative information as described in Exhibit 8-11.

8.2.3.5 Watershed Storage Properties and Conditions

It is impossible to characterize a LID watershed without describing the IMPs (e.g., bioretention, cisterns, pocket wetlands, swales) that may provide significant storage in the watershed. In a site level study, however, it is typically necessary to provide a bulk quantification of these practices instead of a detailed description of each practice, which would require obtaining and reporting larger amounts of data. It is therefore recommended to characterize the volume of storage integrated into a LID site as a set of bulk watershed attributes by quantifying the storage volume and its related characteristics and describing how storage is regenerated after a storm event. These are described below.

Quantify the Effective Storage Volume. Estimate the volume of storage available on the site that is effective in storing stormwater, and divide this estimate between storage volume that is retained and does not discharge to the surface and storage volume that is detained and discharges back to the downstream system via underdrains or discharge structures. If the overall site water balance is an important feature in a study, the storage that is retained can be further divided by the ultimate fate of the retained water: infiltration, evapotranspiration, or exportation off-site (e.g., toilet flushing). The quantity and distribution of storage volume has important theoretical influence on the amount of stormwater expected to discharge from the site.

The concept of “hydrologically available temporary storage” can be used to describe the storage volume of a LID site. Hydrologically available temporary storage at the site potentially includes the following components:

- Surface storage (e.g., natural, pervious, and impervious depression storage; surface retention) that is not surface discharged. This represents volume that is eventually lost through evapotranspiration and/or infiltration but would not have become surface discharge.

- Surface storage (e.g., natural, pervious, and impervious depression storage; surface detention) that is eventually surface discharged after detention and/or infiltration occurs whereby slowing the surface discharge.

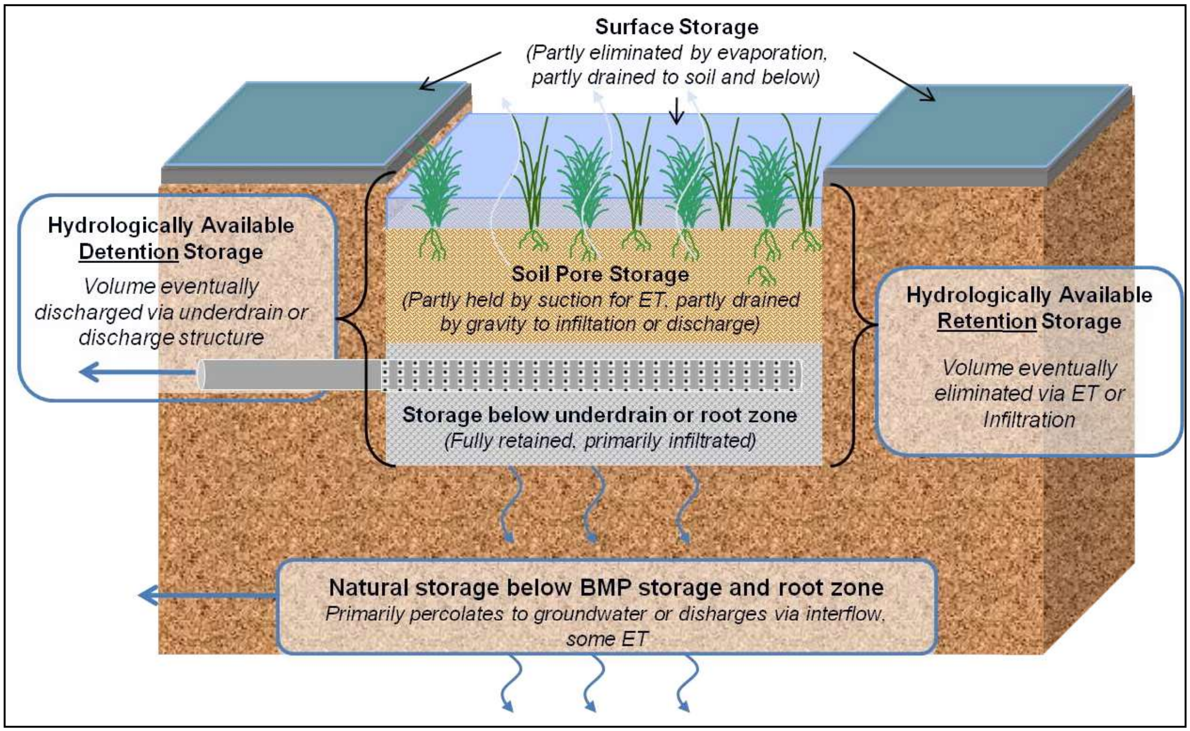
- Subsurface LID practice temporary storage, including all pore space within LID practices (e.g., in bioretention soils, stone infiltration trenches, planter media, green roof media) that is not surface discharged. This also represents the volume that is eventually recovered through evapotranspiration and/or infiltration, but would not have become surface discharge.

- Subsurface LID practice temporary storage, including all pore space within LID practices (e.g., in bioretention soils, stone infiltration trenches, planter media, green roof media) that is eventually surface discharged via an underdrain system.

- Volume in cisterns and rain barrels in excess of average long-term retained volume that is eventually recovered through evapotranspiration (e.g., irrigation reuse, cooling water makeup reuse, drip hose), infiltration, and/or export (e.g. toilet flushing use).

Exhibit 8-13 illustrates components of hydrologically available temporary storage that may be present in an individual practice. The location of available storage relative to sources of runoff is a critical aspect in determining the amount of storage that is “hydrologically available” to store runoff. This concept is further described and illustrated in Section 8.2.4.3.

Exhibit 8-13: Components of Hydrologically Available Temporary Storage Typically Present in LID features



<u>Describe How Storage Is Recovered Following a Storm.</u> Different storage elements may regenerate storage at different rates depending on their characteristics. For example, a bioretention facility with underdrains may draw down its stored volume within 12 hours after a storm, while the same storage volume in a cistern used for irrigation may not begin to draw down its stored volume for a few days following an event and may take a week to draw down completely. Drawdown rate is also influenced by season of year, day of the week, and/or other factors. For example, seasonal variations in temperature can affect evapotranspiration and infiltration rates. Seasonal conditions can also affect irrigation demand, thus affecting drawdown rates for rainwater harvesting practices that commonly use harvested water to for irrigation. The day of the week can also affect regenerated storage rates. For example, the demand for captured water used for indoor toilet flushing in a commercial office building would be expected to be greater during the business week than on the weekend.

The rate of recovery of storage has important theoretical influence on the hydrologic response of watersheds, specifically LID watersheds, in consecutive events. While storage recovery rate is an important component of watershed characterization, it is can be difficult to quantify for a composite site. It is also perhaps one of the aspects of watershed characterization most unique to LID watersheds, and thus has not been well standardized and demonstrated.

Potential methods of standardizing these aspects are discussed in the following section.

8.2.4 Composite Site Characteristics

When comparing LID (and/or other distributed controls) sites, it is helpful to identify a set of composite site characteristics that quantify the extent/type of LID implemented at a site. An ideal set of composite site characteristics would allow for quantification of the extent of LID at a site so that comparisons could be made among LID sites regardless of size, location, and other environmental factors. Ideally, it would be possible to estimate these characteristics for a site regardless of whether LID techniques have been implemented or whether development has yet occurred. For the purpose of this manual, composite site characteristics have been categorized as simple indices and integrated indices, as described below. Hydrologic performance metrics are also proposed as a means of quantifying the extent/type of LID implementation.

Some of these indices/metrics are easier to obtain than others, and some may be better suited to certain types of studies than others. While the indices/metrics listed below have limitations recognized limitations, each of these, or some variation of these, may provide valuable input on a LID site study.

The current body of knowledge does not provide sufficient forum to test these metrics in order to establish their strengths and limitations, therefore broad lists are provided below for consideration. Inclusion on these lists does not necessarily constitute an endorsement by the EPA or the authors of this manual. Likewise, these lists are not exhaustive.

The BMP Database will allow users to input and describe any combination of indices and metrics they choose, however the authors recognize the value that would be added through standardization of site characterization methods. A standardized reporting method can be found in Section 8.2.4.3.

8.2.4.1 Site Characterization Indices

Simple Indices

The following simple indices incorporate watershed characteristics individually or in simple combinations. They are often easy to estimate and may be sufficient to adequately describe simple LID scenarios, especially if multiple simple indices are provided. However, they are not likely to be sufficient to characterize complicated LID scenarios because they do not consider theoretically-important interactions between the various watershed characteristics. Potential simple indices include:

- Total hydrologically available temporary storage in LID features and the percentage split between retained and detained storage in these features.

- Total hydrologically available temporary retained storage relative to average storm depth.

- Maximum, minimum, and/or average time to recover LID feature storage from completely full.

- Average time to fully recover LID storage relative to average inter-event time.
- Estimated volume of pore space within the natural duff layer, compost, mulches, or similar techniques.
- Area weighted saturated hydraulic conductivity and available water capacity of the top foot of native or post construction soils not within LID features.
- Percentage splits of impervious area between impervious area flowing to pervious areas, flowing to LID features, canopy covered only, and directly connected.
- Average ratio of "disconnected" impervious area to pervious area receiving runoff from disconnected impervious area.
- Maximum, minimum, and annual average potential vegetative canopy interception.
- Computed time of concentration of watershed under a range of rainfall intensities (computed by standard method such as Soil Conservation Service Technical Release 55[TR-55]).
- Computed average time of concentration to a hardened conveyance (computed by standard method such as TR-55).
- Area or length of vegetated conveyance per acre of road.

Integrated Indices

Integrated Indices would attempt to integrate multiple watershed characteristics to better describe LID implementation in complex scenarios (i.e., several different LID strategies in the monitored watershed). Such indices would likely require more effort to develop and require more judgment on the part of the study investigator when assigning some input parameters. However, integrated indices could potentially provide a more comprehensive description of the factors likely to affect LID site performance. Preliminary concepts for integrated indices include:

- Spatially-coupled source/sink analysis. Each element of hydrologically available temporary storage at the site would be compared to the cumulative area tributary to each element and the runoff potential of this area. This index could be effective in describing the surface discharge from a watershed in a given storm with given antecedent conditions. If coupled with local rainfall depth statistics and average antecedent conditions, this index could potentially be correlated to average discharge volumes.
- Temporal demand/capacity analysis. The total hydrologically available temporary storage at the site would be assumed to be evenly distributed around the site, and emphasis would be place on the detailed regeneration pattern of each element of hydrologically available temporary storage in comparison to local precipitation

patterns. This index could be more effective than the spatially-coupled source/sink analysis described above if sources and sinks were fairly uniformly matched and if antecedent conditions could not be well summarized with simple statistics. It could potentially be correlated to average discharge volumes and/or frequency of discharge.

It is recognized that any attempt to integrate the broad range of watershed characteristics into a single index would be limited and likely useful at a planning level only. The details of calculating the index (or indices) would need to be developed based on theoretical considerations and on the analysis of studies; however such efforts have yet to be documented.

Regardless, incorporation of a spatial component of study documentation is critical to further the field of study. However, spatial data are not easily summarized or standardized for entry to a database. In the future, the concepts of a graphical interface to standardize spatial data entry or a standardized model development protocol should be investigated. For example, model input files from the EPA Stormwater Management Model (SWMM) could provide a more efficient method of documenting information about spatial relationships and watershed routing than if these watershed descriptions were entered into individual database fields. At this time, it is recommended that detailed PDF figures of the study area be included with user input. Graphical documentation should attempt to illustrate:

- LID practice types.
- Impervious area tributary to each practice type.
- Area and location of each practice.
- Retention and detention volume provided in each practice.
- Storage recovery characteristics of each practice for retention and detention storage (e.g., time to recover 50 percent of storage, time to recover all storage).
- Routing of flow between practice types (e.g., downspout disconnects flow to bioretention if capacity of lawn is exceeded).

8.2.4.2 Hydrologic Performance Metrics

Another way to compare LID sites is to treat certain hydrologic performance metrics as indicators of the extent of LID present at a site and of how well the site is performing, even if only partially.

Hydrologic performance metrics used to describe the extent of LID and how well the site is performing might include:

- Largest rainfall event (depth and duration) producing no discharge.
- Long-term cumulative discharge volume per unit rainfall (long-term volumetric runoff coefficient).

- Largest rainfall quantity producing no discharge with a "wet" versus "dry" Antecedent Precipitation Index (API). API is defined as:

  $$API_t = R_{t-1} + k \cdot API_{t-1} \qquad \textbf{Equation 8-1}$$

  Where:

  API_t: index for day t
  API_{t-1}: index for the previous day
  R_{t-1}: rainfall depth for the previous day (inches)

  k: coefficient reflecting the relative rate of soil drying

  The value of k can range from approximately 0.85 (sand) to 0.98 (clay). "Wet" is considered to be API > 0.6 and "dry" as API <0.6. (Linsley, Kohler, and Paulhus 1982).

- Average of storm-by-storm volumetric runoff coefficient under wet and dry API.

- Largest rainfall quantity producing no discharge with a varying 7-day antecedent rainfall.

- Peak flow rates for specific average rainfall intensities over the time of concentration. For example if the time of concentration for a site is 10 min, the peak flow rate resulting from an average intensity of 0.1 in/hr, 0.2 in/hr, 0.3 in/hr, and so on over 10 minutes under varied antecedent moisture conditions.

- Hydrograph lag time.

- Time of concentration under varied rainfall intensities and APIs determined from analysis of hyetographs and hydrographs.

The effects of temperature on the performance of infiltration-based practices should be considered in developing and comparing metrics. Temperature is known to have a significant effect on infiltration rate.

Closely related to some of the concepts identified above, Davis (2008) proposed three metrics for describing the restoration of hydrologic conditions by bioretention facilities: 1) the peak flow rate ratio of effluent to influent (R_{peak}); 2) the peak discharge time span ratio of effluent to influent (R_{delay}); and 3) the effluent/influent volume ratio (f_V). These are defined as:

1) $R_{\text{peak}} = q_{\text{peak-out}}/q_{\text{peak-in}}$ **Equation 8-2**

2) $R_{\text{delay}} = t_{q\text{-peak-out}}/t_{q\text{-peak-in}}$ **Equation 8-3**

3) $f_{v24} = V_{\text{out-24}}/V_{\text{in}}$ **Equation 8-4**

Where

$q_{\text{peak-out}}$: peak effluent flow rate
$q_{\text{peak-in}}$: peak influent flow rate
$t_{q\text{-peak-out}}$: time from the beginning of influent flow to peak effluent flow
$t_{q\text{-peak-in}}$: time from the beginning of influent flow to peak influent flow
V_{in}: input stormwater runoff volume to a bioretention cell
$V_{\text{out-24}}$: corresponding outflow volume leaving the cell after 24 hours.

Although these three metrics were developed for bioretention facilities, the concepts could be adapted to evaluate LID sites as a whole. Example application of these metrics to six bioretention sites can be found in Li et al. (2009).

8.2.4.3 Recommended Metrics for Reporting to BMP Database

The list of potential indices and metrics included above may be useful in explaining some aspects of LID site performance and should be considered in developing monitoring studies. The BMP Database will allow for the user to report indices and metrics of his or her choice along with an explanation of how the values were been calculated. There is hope that sufficient data will be reported from LID site studies to facilitate evaluations of various indices and metrics for potential standardization of BMP Database reporting forms in the future.

In the meantime, this section proposes a single standardized method that can be used to characterize a site. This "pilot" approach was developed in order to balance input data requirements with the ability to describe spatial and temporal volumetric properties of LID watersheds. The proposed approach was also developed so that it could be readily incorporated into the existing BMP Database structure. It is based on the concepts of hydrologically available temporary storage and temporary storage recovery time. From these two concepts, the "net instantaneous volume" and "storage recovery time" are derived. These two are described below:

Net Instantaneous Volumes

Net instantaneous volume is a metric based entirely on the distribution of tributary area and storage volume in the watershed. It incorporates the concept of hydrologically available temporary storage, which is the amount of storage that can actually be used during a given event. For example, if 10,000 cu-ft worth of storage was located in the upstream end of a watershed where it only received 3,000 cu-ft of runoff from a given storm event, it would only be 3/10$^{\text{ths}}$ utilized during that event regardless of whether capacity was exceeded in other parts of the watershed. The hydrologically available temporary storage contributed by this unit would be 3,000 cu-ft for this storm event, not 10,000 cu-ft. An over-simplified bulk measure of total watershed storage that combines all storage volume regardless of its tributary area would inaccurately assume the remaining 7,000 cu-ft was available to storm runoff from other parts of the watershed, which is clearly not the case. Hydrologically available temporary storage thus describes the spatial relationship of source areas and storage volume, and is expected to vary with storm depth. Exhibit 8-14 illustrates the concept of hydrologically available temporary storage for a simple example catchment.

The net instantaneous volume method compares the volume incident on a catchment during a hypothetical instantaneous event to the storage volume available in the LID practices to which these areas drain. An instantaneous volume is applied over the catchment. The corresponding volume is then transferred to the LID practice receiving runoff from each catchment area. If a LID practice storage volume is exceeded by this volume, excess volume may be transferred to any capacity remaining in downstream practices. For example, if the capacity of a lawn to absorb runoff from a disconnected downspout was predicted to be exceeded by a certain rainfall depth, excess volume could be applied to a street-site bioretention cell. After all hydrologically available storage in the watershed is full, the remaining volume is considered to be the **net excess volume**. All pervious area is considered to be an LID practice, only contributing to runoff if its capacity is exceeded, either by run-on from impervious area or lack of capacity to absorb more volume. The investigator will likely need to use best professional judgment to estimate the storage capacity of pervious areas.

Each LID practice volume is divided between retention volume (i.e., volume that does not discharge to the downstream system) and detention volume (i.e., volume that is captured, treated, and released to the downstream system). Retention volume used during the instantaneous volume calculation is reported as net retained volume. Detention volume used during the instantaneous volume calculation is reported as net detained volume. These two volumes added to the net excess volume should be equal to the total rainfall volume over water area in the hypothetical event.

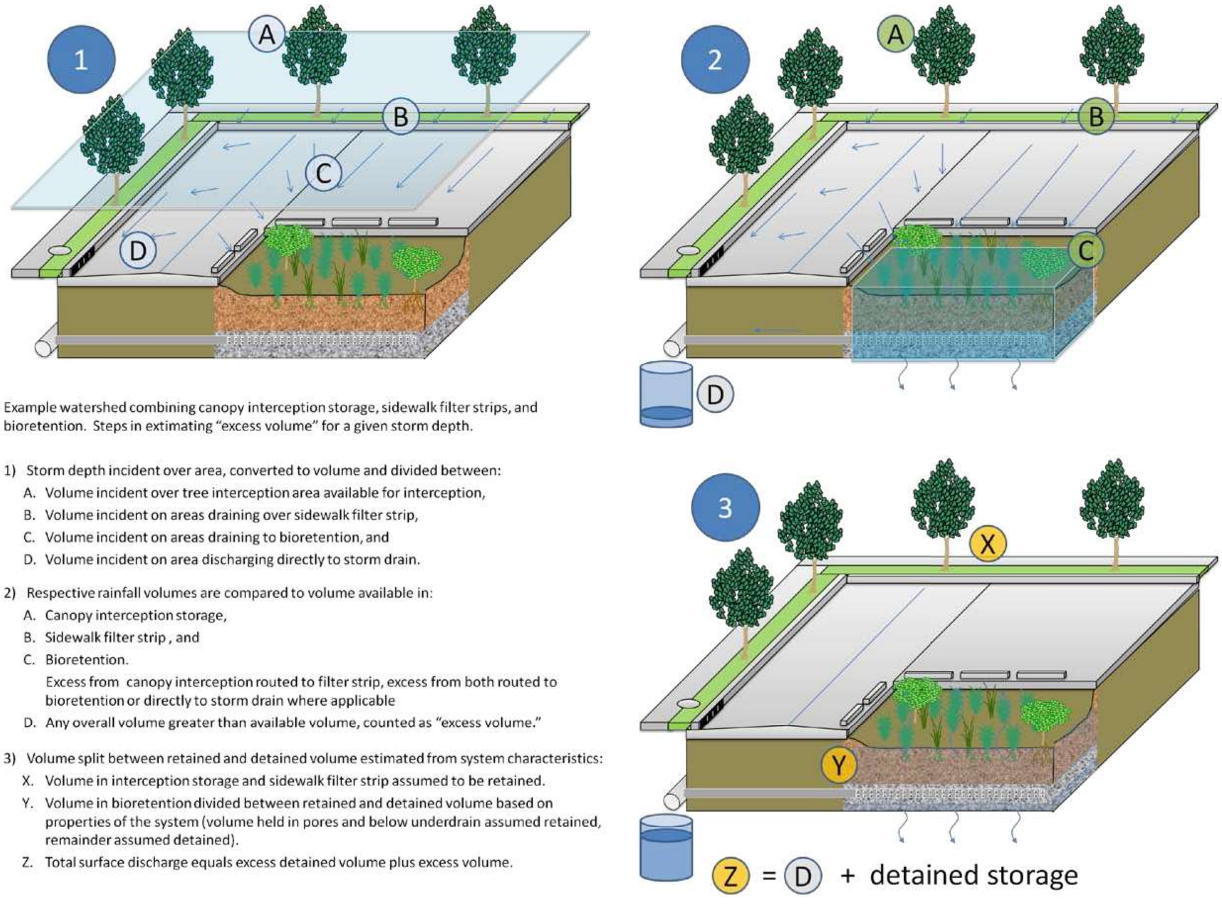
Note the following when computing the net excess volume metrics: (1) Include directly connected impervious areas (i.e., areas not draining to a LID practice) as these areas always contribute to net excess volume because, by definition, no storage exists downstream of DCIA; and (2) Recovery of capacity during the duration of the event is not considered in computing this index. For example, infiltration under LID practices and hydrograph routing through detention facilities should not be considered. The effect of storage recovery is accounted for in the storage recovery rate, described below.

Storage Recovery Rate

The storage recovery rate is a metric that complements the net excess volume metrics described above. The storage recovery rate describes the rate at which hydrologically available temporary storage is recovered. It is defined as the time it takes to recover the hydrologically available temporary storage from brim full. The user may enter seasonal minimum, average, and maximum recovery times. Seasonal factors are expected to influence evaporation-based practices the most, thus minimum and maximum recovery times are strongly suggested where an LID site relies strongly on evapotranspiration-based practices. Storage recovery times should be estimated assuming no additional rainfall.

Conceptual steps in computing excess volume are demonstrated in Exhibit 8-14 for an example parking lot catchment containing the LID practices: interception storage, sidewalk filter strips, and bioretention. Steps are provided for computing excess storage for a given storm depth.

Exhibit 8-14: Conceptual Excess Volume Calculations for a Hypothetical Catchment



Example watershed combining canopy interception storage, sidewalk filter strips, and bioretention. Steps in extimating "excess volume" for a given storm depth.

1) Storm depth incident over area, converted to volume and divided between:
   A. Volume incident over tree interception area available for interception,
   B. Volume incident on areas draining over sidewalk filter strip,
   C. Volume incident on areas draining to bioretention, and
   D. Volume incident on area discharging directly to storm drain.

2) Respective rainfall volumes are compared to volume available in:
   A. Canopy interception storage,
   B. Sidewalk filter strip , and
   C. Bioretention.
      Excess from canopy interception routed to filter strip, excess from both routed to bioretention or directly to storm drain where applicable
   D. Any overall volume greater than available volume, counted as "excess volume."

3) Volume split between retained and detained volume estimated from system characteristics:
   X. Volume in interception storage and sidewalk filter strip assumed to be retained.
   Y. Volume in bioretention divided between retained and detained volume based on properties of the system (volume held in pores and below underdrain assumed retained, remainder assumed detained).
   Z. Total surface discharge equals excess detained volume plus excess volume.

BMP Database input requirements are shown in Exhibit 8-15.

Exhibit 8-15. Composite Site Characterization Inputs to BMP Database

Field	Description
Net **detained** volume – by event	Calculated by user based on storage volume, routing, and event depth as described above. Entered for storm depths selected by user. Recommended that the user provides calculation results for at least three representative depths.
Net **retained** volume – by event	
Net **excess** volume – by event	
Minimum time to recover retained storage	Calculated as the composite time to recover **retained** storage from brim full. Minimum and maximum should account for temperature and other seasonal factors. Recovery may be asymptotic in which case recovery of approximately 90 percent of volume can be considered full recovery.
Average time to recover retained storage	
Maximum time to recover **retained** storage	
Minimum time to recover **detained** storage	Calculated as the composite time to recover **detained** storage from brim full. Minimum and maximum should account for temperature and other seasonal factors. Recovery may be asymptotic in which case recovery of approximately 90 percent of volume can be considered full recovery.
Average time to recover **detained** storage	
Maximum time to recover **detained** storage	
Methods of estimating above parameters (narrative)	User describes methods used to estimate parameters above, including any supporting documentation.

8.2.5 Hydrologic Characterization

A primary purpose of LID site monitoring is to develop a comprehensive hydrologic characterization of the entire site. Consequently, the design of a monitoring plan must consider all of the major processes of the hydrologic cycle that influence the performance of the LID site. Direct site monitoring coupled with locally available meteorological data allows for the development of a reasonably accurate water balance that accounts for area-specific precipitation, infiltration, runoff, evapotranspiration, and storage (soil/media retention of moisture). Additionally, water balances can also be developed for individual LID practices. The following subsections describe the elements of the water balance approach used to measure or estimate these components, and discuss the importance of long-term monitoring and data representativeness.

Monitoring data may be used in conjunction with data from other sources to estimate water balances and characterize general site hydrologic conditions. The National Oceanic and Atmospheric Administration (NOAA), for example, maintains the most comprehensive nationwide datasets of meteorological data. It is available through the National Climatic Data Center (NCDC) website (http://www.ncdc.noaa.gov). Some of the relevant data available from NCDC include:

- Wind speed and direction
- Temperature
- Solar radiation
- Precipitation

These data may be available as hourly, daily, or monthly values depending on location.

Evapotranspiration data can also be consulted. These data are most often found on websites maintained by state and regional agricultural agencies that monitor and report this type of information. Some suggestions are: California Irrigation Management Information System (CIMIS) (http://www.cimis.water.ca.gov), Arizona Meteorological Network (http://ag.arizona.edu/azmet/azdata.htm), University of Virginia Climatology Office (http://climate.virginia.edu/va_pet_prec_diff.htm), and Pacific Northwest Cooperative Agricultural Network (AgriMet, U.S. Bureau of Reclamation, http://www.usbr.gov/pn/agrimet/).

8.2.5.1 General Water Balance

A water balance can be described as an accounting of water inflow and outflow to determine change of storage in a system or control volume. A system is defined as any physical domain in space, such as a large regional watershed, an urban catchment, or a specific soil layer or matrix underneath the surface. Defining a water balance partitions the quantity of water into individual mechanisms, which helps build an understanding of the mechanisms that determine the fate of water. This allows the magnitude of treatment between individual processes to be understood. Equation 8-5 summarizes the basic water balance equation:

$$\sum V_{in} - \sum V_{out} = \Delta S$$ **Equation 8-5**

Where:

V_{in}: total inflow volume over some time period Δt

V_{out}: total outflow volume over some time period Δt

ΔS: change in total storage volume over time Δt

Inflows may include direct precipitation, surface runoff, or groundwater exfiltration. Outflows may include infiltration, evapotranspiration, and surface discharge (treated and bypassed). System storage may include interception on plant surfaces, surface ponding, and water held in soils.

With respect to a LID site, a water balance system can be defined based on the objectives and spatial extent of the monitoring project. This can vary from individual LID practices to the cumulative estimated effect of all the LID practices at the watershed's outlet.

As a first step in developing a water balance, flow paths that affect the water balance of a system should be identified in order to organize the monitoring study and to fulfill the study objectives. In general, all inflow, outflow, and system storage variables should be monitored. However, it is typically not feasible or even possible to monitor all of these directly, in those cases the variables should be estimated using indirect methods. At a minimum, most LID monitoring sites should directly monitor rainfall and outflow from the site. Infiltration and evapotranspiration are more difficult to measure directly, but can be estimated by conducting infiltration tests, measuring changes in water level, or using soil moisture profiles to track the wetting front. In order to estimate evapotranspiration, more sophisticated LID monitoring studies can employ weather monitoring stations that record a full suite of meteorological variables such as precipitation, wind speed and direction, temperature, relative humidity, barometric pressure, and soil moisture. With the increasing popularity of "smart" irrigation controllers, "real-time" evapotranspiration data may also be available in some areas from local water utilities or vendors that provide services for such irrigation controllers. Several approaches can be used to develop a water balance using a combination of measured and estimated data. These approaches are described below.

8.2.5.2 Regional Water Balance

Evapotranspiration and infiltration are key water balance components of LID practices. These factors need to be estimated rather than measured directly as they depend on meteorological conditions (e.g., temperature, humidity, wind speeds), soil properties (e.g., field capacity, hydraulic conductivity), and vegetative cover.

The average evapotranspiration of a watershed can be estimated using Equation 8-6. It shows the regional water balance for a single catchment (Dingman 2002). While looking at a site's long-term water balance and consulting Exhibit 8-16, it may be possible to assume that groundwater fluxes in and out cancel each other out, on average, and that the change in storage is negligible over a long period of time. With these assumptions, an average evapotranspiration can be calculated by subtracting the average flow from the average precipitation. Although this is a simplistic method, it provides a general indication of the effects of soil soaking and drying across the watershed.

$$P + G_{in} - (G_{out} + Q + ET) = \Delta S$$ **Equation 8-6**

Where:

P: rainfall
G_{in}: groundwater flux into the control volume
G_{out}: groundwater flux out of the control volume

Q: surface flow
ET: evapotranspiration
ΔS: change in storage

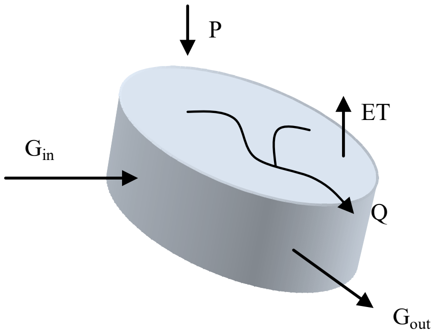


Exhibit 8-16. Components of the Regional Water Balance Equation (Dingman 2002)

8.2.5.3 Thornthwaite Monthly Water Balance

The Thornthwaite monthly water balance is a lumped, conceptual model that estimates evapotranspiration from potential evapotranspiration (PET) and tracks monthly water balance volumes using a simple soil-moisture accounting procedure. Assuming the maximum soil moisture capacity, ϕ, can be estimated for any amended soil areas and non-amended soil areas of a LID study watershed, the monthly depletion and regeneration of the soil moisture can be estimated using monthly rainfall measurements, P_i, and monthly PET, PE_i, estimates. Moisture surplus, Q_i, occurs whenever the actual soil moisture, S_i, exceeds its capacity. This surplus translates to either runoff or groundwater recharge. If monthly runoff volumes, R_i, are available for the watershed, the monthly volume of soil moisture surplus infiltrating to groundwater, G_i, can be estimated. This method incorporates the moisture surplus in the previous month, Q_{i-1}, and the actual soil moisture in the previous month, S_{i-1}. The following Thornthwaite monthly water balance equations (all in units of depth) have been adapted from Alley (1984):

$$S_i = S_{i-1} \exp\left(\frac{-(PE_i - P_i)}{\phi}\right)$$ **Equation 8-7**

$$\Delta Q = \begin{matrix} (P_i - PE_i) + S_{i-1} - \phi \\ 0 \end{matrix} \quad \text{if} \begin{cases} S_i = \phi \\ S_i \neq \phi \end{cases}$$ **Equation 8-8**

$$G_i = Q_i \left(1 - \frac{R_i - \Delta Q}{Q_{i-1}}\right)$$ **Equation 8-9**

Where:

S_i:: soil moisture
S_{i-1}: soil moisture for previous month

P_i: monthly rainfall
PE_i: monthly PET
ϕ: maximum soil capacity
ΔQ: moisture surplus
Q_i: monthly moisture surplus
Q_{i-1}: monthly moisture surplus for previous month
R_i: monthly runoff volumes
G_i: monthly volume of soil moisture surplus infiltrating to groundwater

Values estimated for a certain month depend on those of the previous month, so models using climatic average values should be iterated until equilibrium values are reached. Actual monthly time series are preferred if available. Soil moisture capacity can be estimated as the difference between the field capacity and the wilting point multiplied by the depth of the root zone. These soil properties can be obtained from soil survey data or estimated by experimentation. Monthly PET can be estimated using a reference crop coefficient method or the Penman-Montieth equation as described below in Section 8.3.3.2. For a LID site with multiple distributed practices, the monthly water balance would need to be computed for each practice as well as for the remaining pervious areas of the site. The remaining pervious areas should be divided based on whether they have been impacted by construction and whether they have been restored or amended. Estimates of monthly runoff volumes from impervious surfaces would also need to be accounted for in the water balance. Impervious areas draining to LID practices would need to be carefully estimated and the monthly runoff contributions would need to be accounted for using an appropriate hydrologic method.

In areas with snowfall, temperature data are needed to estimate the snow melt and the buildup of snow pack. Dingman (2002) describes a simple procedure for using a temperature index model to account for the contribution of snow melt. Exhibit 8-17 illustrates the monthly water balance method with consideration for snow melt as proposed by Dingman (2002) for three U.S. cities. The Atlanta, GA water balance shows a relatively constant amount of water input in the form of precipitation (rainfall) throughout the year. There is sharp a decrease in the soil moisture during the heat of the summer months, ostensibly due directly to a dramatic increase in evapotranspiration. There is, however, a soil moisture surplus that occurs in the mild winter months. Omaha, NE, on the other hand, receives its rainfall primarily in the late spring through early fall. A significant amount of snow pack occurs in the winter months and there is a fairly abrupt peak in soil moisture late in the spring that quickly drops down to a low and constant value by the end of summer. In stark contrast to both Atlanta, GA and Omaha, NE, Portland, OR receives nearly all of its water input from late fall through the spring, with very little precipitation throughout the summer months.

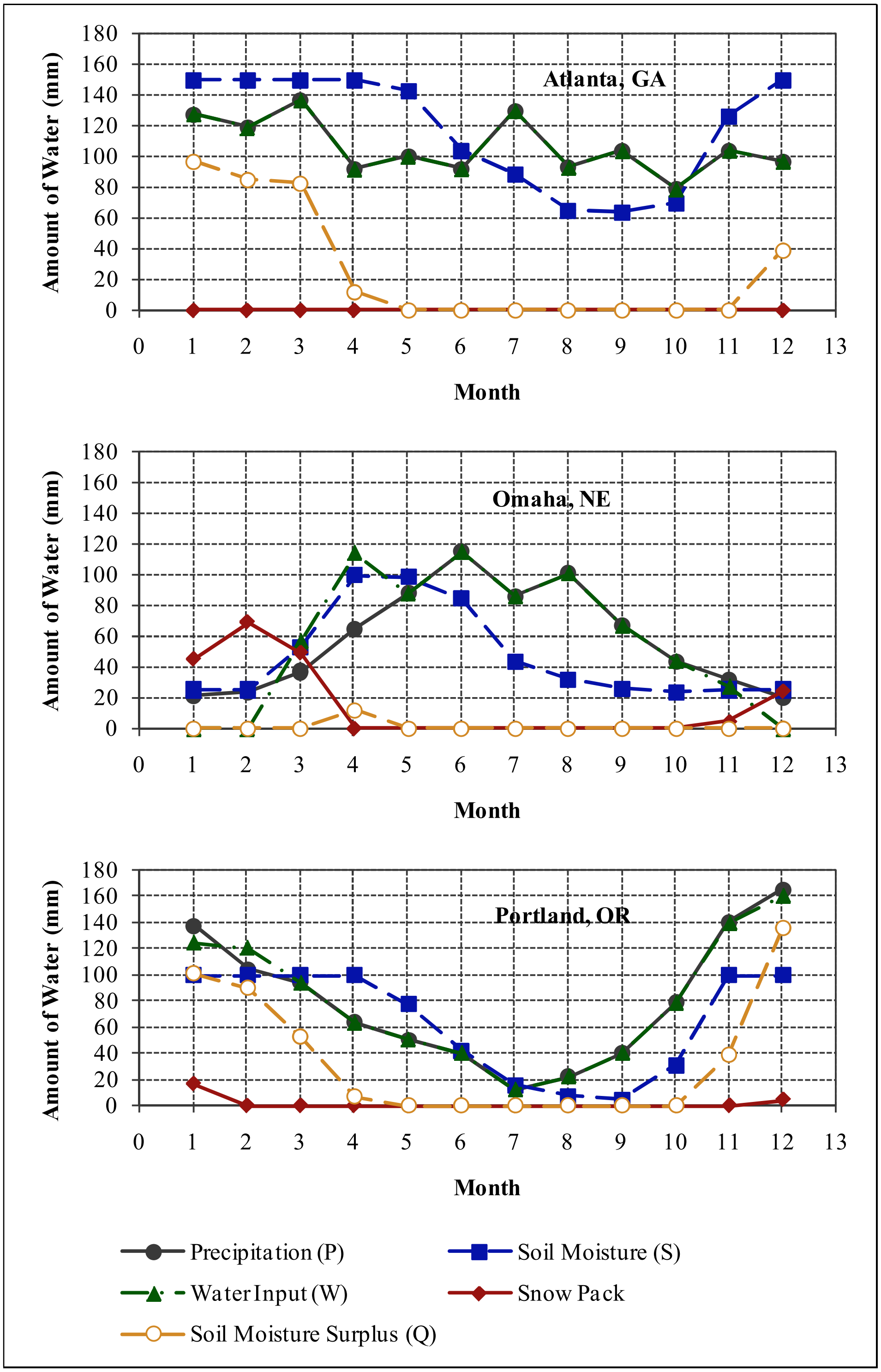


Exhibit 8-17. The Thornthwaite Monthly Water Balance of Three U.S. Cities

8.2.5.4 Long-Term Monitoring and Data Representativeness

When sufficient funding is available for LID monitoring projects, long-term monitoring (e.g., 5 to 10 years) should be seriously considered. Some of the benefits of long-term monitoring of LID sites include:

1) Long-term monitoring helps answer many questions that persist about the effectiveness of LID practices seasonally and over time, as opposed to short term LID monitoring which only provides limited information about the immediate response of the LID catchment.

2) Long-term monitoring helps determine the long-term water balance for a LID catchment and allows for a greater likelihood that hydrologically representative conditions have occurred.

3) Long-term monitoring increases the number of data points, which helps decrease uncertainty due to measurement errors or the collection of unrepresentative storms or seasons. By increasing the data points, long-term monitoring increases the potential meaningfulness of the comparisons that can be made between watershed conditions before and after LID practices are implemented.

4) With multiple sites containing different LID concepts, long-term monitoring facilitates confident comparisons of treatment efficiency between different test sites.

If long-term monitoring is not feasible due to budget constraints, then care must be taken to characterize the hydrologic conditions under which the sampling is conducted so that collected data from appropriately similar events, or periods within events, are compared. Important hydrological conditions to record are total rainfall depth, average and peak intensity, duration, and preceding inter-event time. These data should be interpreted in the context of the local meteorological patterns. To provide context for monitoring results, it may be useful to estimate the recurrence interval of various characteristics of a monitored storm or to estimate the cumulative contribution of additional storms (i.e., storms that are smaller than or equal to the monitored storm) to the overall rainfall. However, in order to compute these metrics, professional judgment is required as well as an in-depth knowledge about how these metrics will be used to support the study assumptions. In order to reduce problems associated with misinterpreting the data or disparity in methods, these metrics are not requested for input into the database. Instead, only directly measured storm characteristics are requested in the database.

Regardless of whether long-term monitoring is feasible, the usefulness of intra-event measures of performance should be strongly considered to evaluate LID performance (e.g., depression storage, peak lag, changes in time of concentration, slopes of rising and falling hydrograph limbs). As introduced in Section 8.1.3, high-resolution intra-event data may also permit the calibration and validation of continuous simulation hydrologic models that can be used to develop estimates of runoff patterns and long-term hydrologic performance extending well beyond the period of monitoring.

8.3 Data Collection and Reporting

Data collection and reporting for LID studies generally follow the same protocols as those discussed in Chapters 2 through 6 for traditional BMP studies. However, LID studies place more emphasis on documenting the watershed characteristics, as well as the infiltration and evapotranspiration components of the water balance. Following a brief overview of the BMP Database approach to reporting LID, additional guidance is provided about the approaches to characterize impervious area as well as directly and/or indirectly quantify evapotranspiration and infiltration at the site level. Additionally, due to national interest in the costs of LID relative to traditional development, guidance for reporting LID cost information is also provided.

8.3.1 BMP Database Requirements for LID

LID monitoring data requirements for the BMP database are being revised in 2009 and are provided in draft form in Appendix A. These revisions expand the 2008 structural changes that have already enabled incorporation of LID at the overall development level. Examples of features of the database enabling entry of LID studies include:

1) Test Site. An individual test site or monitoring study can include data for multiple test and reference watersheds. PDFs containing detailed photography or geographic information system (GIS) maps to clearly define the spatial location of LID practices in the watershed can be uploaded with the study. These should include an annotation of land treatment (e.g., unimpacted, disturbed, restored, amended soils) and a graphic display of routing patterns (e.g., flow paths of disconnected impervious area over pervious area, delineation of tributary area to IMPs). Additional guidance in preparing these figures/datasets is provided in the User's Guide accompanying the BMP Database Data Entry package.

2) Watershed information. Many watershed characteristics important for documenting LID studies are already included in the BMP Database as described in Exhibit 8-7. Additional fields have been added as part of this revision to more adequately characterize LID watersheds. In the case of nested studies, for example, the same LID feature can be entered into the database differently depending on whether it is one of many components in a site level study or whether it is the focus of a practice level study. In the former case, individual practices are not entered separately, but rather as a part of watershed characteristics. In the latter case, the individual practices can be entered as described in Chapters 1 through 7. (For more information, consult "Specific BMP Information" in number four below.) The BMP Database facilitates the documentation of practice level studies within site level studies. New data requirements are described throughout this chapter and are compiled in Appendix A.

3) General BMP information. General BMP information can be entered for multiple BMPs (including LID techniques) in each watershed monitored. Additionally, researchers can enter a "treatment train BMP" to represent the performance of multiple BMPs in series or a LID watershed draining to a centralized BMP. The 2009

revisions to the BMP Database request additional information on parameters such as maintenance, basis of design and other parameters.

4) Specific BMP information: Reporting parameters for specific individual LID practices are included in the 2009 revisions to the BMP Database for bioretention, green roofs, stormwater harvesting (cisterns), permeable pavement, and site level LID, as summarized in Appendix A. Additional guidance related to nomenclature is provided in the User's Guide accompanying the BMP Database Data Entry package.

5) Monitored events: Reporting requirements generally remain the same as the previous version of the BMP Database; however, finer resolution monitoring can allow researchers to accurately capture the relatively lower flows and durations of flows expected to occur in small subcatchments with LID practices. The total duration of LID monitoring events should be carefully considered because LID practices utilize mechanisms that have larger time scales for treatment (i.e., evapotranspiration and infiltration). Event monitoring duration should be representative of the time scale of the treatment and any temporal changes that might affect treatment, such as seasonal effects. If continuous hydrologic records are obtained, data can be reported for individual events within the record or for longer timescales (i.e., by month or by season). As long start and end recording times are accurately entered for each study, reporting of overlapping periods is acceptable. In fact, recording overlapping periods may even enable a more robust interpretation of results.

6) Monitoring stations and monitoring results: Flow and water quality monitoring results for LID practices is the same as the previous version of the BMP Database. Additional fields for user estimates of the infiltration and evapotranspiration volumes over the duration of the monitoring study may be provided to complete the water balance. (Exhibit 8-18)

7) Subsurface Water Quality: If subsurface water quality is monitored, the user can report the quality of infiltrated water reaching groundwater. The user may enter event mean concentrations for a specific monitoring point, average annual concentrations for either a specific monitoring point or for the entire LID site, and/or estimated total annual pollutant load.

8.3.2 Impervious Surface Data Collection

Quantifying the overall imperviousness of a watershed or a LID study area can be done using a number of techniques such as direct measurement, digitization, or analysis of remotely sensed data. The method chosen depends largely on the size of the study area and available budget.

Direct measurement is the most accurate and the most labor intensive method for estimating imperviousness. All impervious surfaces (e.g., roadways, roof tops, driveways) within the area of interest must be discretely measured using either a global positioning system receiver or a surveyor's total station. For very small areas, an engineer's level and a tape measure can suffice.

Digitization is another method for estimating imperviousness. This method involves delineating impervious surfaces using aerial photographs, satellite images, development plans, as-built drawings, or other spatial data sources that accurately and clearly depict the land cover. Digitization is best done using GIS software. The accuracy of digitization is a function of the spatial and spectral resolution of the data, as well as the accuracy (and meticulousness) of the digitizer and/or robustness of the digitizing algorithms. If aerial photographs or satellite images are used, the impervious surfaces may be partially or fully obscured by mature trees or other vegetation which may also affect the accuracy of the digitization process. However, it should be noted that impervious surfaces with canopy (ISWC) would not have the same hydrologic response as impervious surfaces without canopy (ISWoC) because a significant amount of rainfall could be intercepted on the leaves and stems of trees. If a study area has significant vegetative cover over impervious areas during the wet season, then both the ISWC and ISWoC should be estimated and reported. When interpreting these data, however, note that the amount of water intercepted in tree canopies may depend on the intensity of rainfall and the strength of wind.

More automated and accurate methods for estimating impervious surfaces using GIS techniques are also possible with the increased availability of high-quality, remotely-sensed data, such as multi-spectral satellite imagery, panchromatic aerial photography, and light detection and ranging (LiDAR) data, Rogers et al. (2004) used QuickBird satellite data (4-band including near-infrared and true-color) and the Feature Analyst™ extension for ArcGIS™ to identify pervious and impervious areas at the sub-meter level in a study conducted in Santa Barbara County, CA. This study found that the method was 91 to 95 percent as accurate as the manual digitization yet required only a fraction of the labor involved. Similar to digitization of aerial photos, this method only captures ISWoC. Hodgeson et al. (2003) developed a rule-based approach for classifying impervious and pervious surfaces using a combination of high resolution color imagery and LiDAR data that helped identify the height and density of vegetation. This approach resulted in an estimated percent error of 6 to 10 percent. The authors noted that if near-infrared band data had also been included (as in the Rogers et al. study), the estimated percent error may have been less because surfaces within shadows could have been more accurately identified. While more research in the field of digital image processing and spatial data analysis is needed, the high quality data and analytical tools that are currently available allow for cost effective and reasonably accurate estimates of impervious surfaces.

In addition to using these techniques for estimating total impervious area, it is also important to estimate the breakdown of impervious surfaces between directly connected impervious area, area draining to IMPs, and areas that are disconnected via a sheet flow over pervious surfaces. While these estimates are critical for comparative evaluations of LID sites, they can be extremely difficult and tedious to obtain especially for large areas. These estimates are most accurately obtained by direct field assessments of land surfaces and drainage features. For large sites, statistical sampling methods can allow a number of small survey areas to be extrapolated to study level averages. Alternative methods may also include manually analyzing elevation data within computer-aided design or GIS software or using flow direction and flow accumulation procedures within a GIS. Note that rooftops are not well represented using these methods.

8.3.3 Hydrologic Data Collection

The collection of hydrologic data is needed to quantify all elements of the water balance over a specified monitoring period. As discussed above, precipitation and flow monitoring is not significantly different for an individual BMP as it is for an overall LID site. Therefore, the discussion of flow monitoring techniques provided in Chapter 3 is not repeated here. Instead, methods for quantifying infiltration and evapotranspiration, the two most important processes for LID sites, are discussed in detail below. Although development of a precise water balance is likely unrealistic at most sites, it is important to develop at least an approximate understanding of basic water balance components.

8.3.3.1 Quantifying Infiltration

The infiltration rate is a measure of the rate at which soil is able to absorb water during a rainfall-runoff event. Monitoring the subsurface hydrology of a LID site can help determine both the infiltration and subsurface runoff portions of the water balance. Subsurface flows can be estimated using the basic principles of Darcy's Law along with the hydraulic conductivity and piezometer data measured manually or over time with pressure transducers. Lysimeter data should also be collected where possible to monitor soil moisture. Likewise, any shallow bedrock or aquitard layers should be identified. Possible methods and instruments used to determine the bulk infiltrative properties of soils are discussed in the paragraphs below.

Soil Survey Data

The Natural Resource Conservation Service (NRCS) is a federal agency that provides free or low-cost soil survey data. Field Office Technical Guides provide basic soils and soil conservation information about a region. The NRCS website (http://www.nrcs.usda.gov) also provides electronic datasets for use in GIS applications from several federal agencies (e.g., USGS, US Census Bureau). The datasets contain information about the basic soil types and distributions. This information can be used to estimate soil properties, such as infiltration and field capacity, and appropriate site comparisons. These characteristics affect the sponge factor of the site. A general LID design principle is to preserve soils with naturally high infiltration capacities, opting instead to disturb those that are less pervious.

Lab Classification of Soil Samples

Lab classification of soil samples can also be an effective way to estimate infiltration rates. When using this method, care should be taken to obtain samples at sufficient horizontal and vertical resolution in order to adequately characterize the variability of soil properties. This is especially important when conducting a site level study. Various methods of extrapolating soil properties and infiltration rates exist. Estimating *in situ* infiltration rates should be conducted to whatever degree possible.

Ring Infiltrometers

Ring infiltrometers are impermeable rings that can be used to measure the vertical infiltration at the ground surface. Either sealed at the ground or slightly inserted into the ground, water is fed into the infiltrometer at a rate which induces ponding. The rate of infiltration can then be calculated by measuring the rate at which the water level falls, the flow rate required to maintain a constant water level, or by solving a basic water balance for the ponding water. Single-ring infiltrometers can lead to artificially high measurements due to horizontal migration of the infiltrating water. To mitigate this, double-ring infiltrometers can be used. While both rings are filled equally with water in a double-ring infiltrometer, the outside ring provides a saturated buffer for the inner ring while data are collected from the inner ring only. While double ring infiltrometers may overpredict infiltration rates compared to what might actually occur if the entire area is saturated during an event, they can still produce useful data. Further discussion about the scientific basis and application of infiltrometers is beyond the scope of this document.

Water Level Observations

Monitoring can be regularly conducted using standard water level indicators. For example, piezometers and monitoring wells can be used to measure the piezometric head of the groundwater system. Pressure transducers can also be employed to continuously record the levels at sampling rates selected by the design team. Implementing these techniques allows scientists and engineers to see how the groundwater responds to storm events, drought periods, and seasonal changes. These same techniques can be used to measure the water level in storage structures and small streams in order to further refine LID site water balance estimates.

Sprinkler Plot Studies

Sprinkler plot studies can be performed on a control parcel of land with vegetation that is representative of the overall site. Constant rainfall is artificially simulated at such a rate that produces the condition of saturation from above requisite for infiltration studies. The difference between the known water input rate (w) and the measured runoff as a function of time (q) is the measured infiltration rate as shown below:

$$I(t) = w - q(t) \qquad \textbf{Equation 8-10}$$

Where:

I: infiltration rate

t: time

w: water input rate

q: measured runoff

Soil Moisture Profiles

Tensiometers can be installed at several depths within a soil profile to measure the moisture content. A tensiometer is a device that contains a tube of water that is sealed off from atmosphere at the top and capped with a porous stone at the bottom. The soil surrounding the device is free to pull water through the porous stone, creating vacuum pressure inside the tube. By monitoring this pressure through time, the moisture content and suction head of the soil can be determined. Tensiometers can indicate a dramatic increase in soil moisture as the wetting front progresses downward. The infiltration rate can then be estimated from those data. Similarly, the drying of the soil profile due to evapotranspiration can be observed.

8.3.3.2 Quantifying Evapotranspiration

Evapotranspiration is the process through which liquid water and ice is converted to water vapor in the atmosphere: surface water can evaporate directly into the atmosphere; plant leaves can transpire water collected by their roots and leaves; and ice can sublimate directly into gas form. The amount of evapotranspiration that occurs at a particular place in time depends on many factors such as the ambient relative humidity, amount of water available to the atmosphere, and the vegetative cover.

Evapotranspiration can be measured with varying degrees of confidence. Consequently, it is important to pair the sophistication of the measurement method with the accuracy required in the study. For example, evapotranspiration is a critical performance factor for green roofs and should be measured with a high level of accuracy. However, evapotranspiration is less important for bioretention BMPs without underdrains because losses tend to be dominated by infiltration. In this case, less sophisticated measurements may be satisfactory. The following paragraphs describe some methods of measuring or estimating evapotranspiration.

It is important to note that equations for estimating evapotranspiration and the coefficients to adjust measured evapotranspiration are generally based on crops growing in fields, and not BMPs. Appropriate consideration should be given to microclimate, vegetation type, and vegetation density in estimating evapotranspiration from BMPs. The Landscape Coefficient Method (University of California Cooperative Extension, 2000) is a recommended method for translating reference evapotranspiration values to evapotranspiration rates of various landscaping.

Potential Evapotranspiration

The potential evapotranspiration (PET) is a measure of the ability of local climate or meteorological conditions to remove water from the surface landscape. Basically, PET is the maximum amount of water an atmosphere can accept from the ground and vegetation below. It does not depend on the amount of water actually present, which if limited would cause the actual evapotranspiration to be less than the PET. PET is often estimated through the use of a reference crop, typically alfalfa or a short grass. The reference evapotranspiration (ETo) represents the PET from the selected reference crop in full sun with constant supply of water, and can be measured with atmometers as discussed in Chapter 3. The measured ETo can be adjusted for different types of vegetation, vegetation densities, and microclimates (University of California Cooperative Extension 2000).

Lysimeters

Weighing lysimeters are vegetated enclosures of soil through which the flow of water (precipitation and drainage) can be measured by determining the mass of the entire enclosure. The evapotranspiration can thus be determined by completing the water balance within the control volume defined by the lysimeter boundary. Typically, the volume of a lysimeter ranges from 1 m^3 up to 150 m^3, though portable ones with areas of 0.2 m^2 are also available. Construction drawings for lysimeters have been previously published in Dunne and Leopold (1978), Brutsaert (1982), and Shaw (1988). Water quality monitoring lysimeters are used to sample water from the pore space in soil, however they do not provide the data needed to estimate evapotranspiration.

Note that some researchers use the term "lysimeter" to refer to devices that measure the suction head of a soil. A tube is typically filled with water, capped at the bottom with a porous stone, and then sealed up top. By measuring the pressure inside the tube, the suction head of a soil can be measured. Throughout this document, these devices are referred to as tensiometers as discussed previously in Section 0. The term "lysimeter" will exclusively refer to the device described in the previous paragraph.

Use of Meteorological Data

Basic meteorological data is required to characterize the hydrologic performance of a site LID. Precipitation data must be available and are preferably collected on site rather than from a nearby weather station because of the significant spatial variation associated with storm events. Precipitation in the form of snow fall should also be carefully considered as the runoff from the event can be delayed by weeks or even months. Additionally, rain events coupled with a thawing snow pack can lead to intense runoff events. Care must also be taken to determine an appropriate snow-water equivalent value; heated and mass-based precipitation gages can facilitate this. Other meteorological quantities such as humidity and wind speed can also be used to estimate the evapotranspiration at a site. While this information can help refine the water balance calculations, it is not necessary for sufficiently accurate estimations.

Pan Evaporation Data

According to Chow et al (1988) and Dingman (2002), evaporation pans are a simple and direct approach used to estimate the free-water evaporation of a site. A cylindrical, open pan of water is used to solve the basic water-balance equation:

$$E_{pan} = W - (V_1 - V_2) \qquad \textbf{Equation 8-11}$$

Where:

E_{pan}: evaporation
W: precipitation
V_1: volume of water at the beginning of study period
V_2: volume of water at the end of study period

The precipitation is measured in an adjacent gage, and the volumes are estimated by recording the water level in the pan. Care must be taken to install protection that prevents animals from drinking or bathing in the water. Similarly, when pans are placed over or near open bodies of water, measures should be taken to prevent water from splashing into the pan.

Due to additional heat absorbed by the metal walls of the pan during evaporative summer months, evaporation is typically overestimated. A calibration factor, or pan coefficient of 0.7 is applied throughout the United States. With the pan coefficient, the free-water evaporation can be estimated with the following empirical equation:

$$E_{fw} = 0.7 \cdot \left(E_{pan} \pm 0.064 \cdot P \cdot \alpha_{pan} \cdot \left(0.37 + 0.00255 \cdot v_{pan}\right) \cdot \left|T_{span} - T_{a}\right|^{0.88}\right)$$ **Equation 8-12**

Where:

E_{fw}: free-water evaporation
α_{pan}: the ratio of energy exchanged through the sides of the pan to evaporation
T_{span}: surface temperature of the water in the pan
T_{a}: temperature of the atmosphere
v_{pan}: wind velocity 15 cm above the pan.

Note: The expression to the right of E_{pan} is added (+) if $T_{span} > T_{a}$ and subtracted (-) if the opposite is true. The value of α_{pan} can be estimated as shown:

$$\alpha_{pan} = 0.34 + 0.0117 \cdot T_{span} - \left(3.5 \times 10^{-7}\right) \cdot \left(T_{spac} + 17.8\right)^{3} + 0.0135 \cdot v_{pan}^{0.36}$$ **Equation 8-13**

Penman-Montieth Equation

Estimating the evapotranspiration of a vegetated surface can be done via the Penman-Montieth equation. It has been widely tested and has been accepted for use over a variety of vegetated land surfaces, though it cannot be applied to bodies of open water. The equation is very data intensive and requires monitoring and calculation of such quantities as humidity, vapor pressure of water in air, atmospheric resistance, and net radiation flux of the ground surface among others. For this reason, Penman-Monteith is typically best implemented with numerical modeling. The equation has the following form:

$$\lambda ET = \frac{\Delta\left(R_{n} - G\right) + \rho_{a} c_{p}\left(\frac{e_{s} - e_{a}}{r_{a}}\right)}{\Delta + \gamma\left(1 + \frac{r_{s}}{r_{a}}\right)}$$ **Equation 8-14**

Where:

R_{n}: net radiation
G: heat flux of the soil
ρ_{a}: density of air
c_{p}: specific heat of air
e_{s}: saturated vapor pressure of air
e_{a}: actual vapor pressure of air
Δ: slope describing the relationship between e_{s} and temperature
γ: psychrometric constant

r_s: surface resistance
r_a: aerodynamic resistance
λ: latent heat of vaporization
ET: mass of water evapotranspired per unit area

To calculate the various quantities required to use the Penman-Monteith equation, the reader should refer to any number of hydrology textbooks such as Dingman (2002).

The PET estimated through the Penman-Monteith equation or with similar equations can be reported in real-time by using weather stations that collect the necessary inputs for those equations. This is a common method, especially when the accuracy of evapotranspiration measurements is not crucial.

8.3.3.3 Reporting of Water Balance Results

The new BMP Database facilitates reporting of water balance results for site level LID studies. Water balance may be estimated based on regional inputs or site level monitoring. In either case, it is recognized that water balance cannot be directly observed and professional judgment is required. Exhibit 8-18 describes the data entry fields associated with water balance.

Exhibit 8-18. Reporting Format for Water Balance Results

Entry Field	Description
LID Watershed ID	This should correspond with the ID entered with the watershed characterization data.
Time Scale of Estimate	The options include: • Discrete monitoring period • Long-term estimate
Start Date (if discrete monitoring period)	This is the beginning of period for which the estimate applies.
End Date (if discrete monitoring period)	This is the beginning of the period for which the estimate applies.
Total Precipitation	This should be entered as totals for discrete monitoring period, or as an annual average water balance for long-term estimate.
Total Evapotranspiration	
Total Surface Discharge	
Total Discharge to Groundwater	
Method of Estimate	This is a user narrative that includes supporting calculations; it is encouraged to be submitted with entry.

8.3.4 Water Quality Data Collection

Water quality monitoring guidance provided in Chapter 4 is also applicable when considering an entire LID site. The same water quality field parameters and pollutants at a LID site should be measured and controlled per applicable local, state, and federal regulations and permits. However, monitoring strategies for LID sites change when monitoring the distributed controls. For example, determining event mean concentrations for runoff events requires accurate flow rate measurements and frequent sampling, often with expensive automated sampling equipment that may be uneconomical to apply to multiple distributed controls. In this scenario, grab samples of surface runoff at locations of interest may be the only feasible monitoring strategy.

Sampling techniques for subsurface water largely depend on the type of water to be monitored. For example, groundwater can typically be pumped from a monitoring well and sampled after a certain purged volume has been removed. Pore water in the unsaturated zone can be extracted by applying vacuum pressure to a tensiometer and sampling the removed water. Tensiometer sampling at increasing depths can track pollutant removal with depth at infiltration-based practices such as rain gardens and roadside swales.

Depending on the study objectives, subsurface water quality data monitoring locations may be strategically selected to monitor critical contamination pathways. Pitt et al. (1994) suggest a three pronged approach for assessing the risk of groundwater contamination based on:

- Abundance of pollutant in stormwater (relative to concentrations of concern)
- Treatability of pollutant through sedimentation (based on dissolved fraction)
- Mobility of pollutant in vadose zone (based primarily on partitioning)

Subsurface monitoring should be primarily focused where runoff concentrations of critical pollutants are high enough to potentially impact groundwater, where treatability of runoff pollutants is low, or where pretreatment of pollutants is limited. This type of monitoring should also focus on areas where the mobility of the pollutant in the vadose zone is high or not well understood.

8.3.5 Cost Data

Currently, many communities have significant questions about the economics of LID and the costs and benefits of LID relative to traditional development practices. The EPA (2007) summarizes the economics of 17 LID field case studies by directly comparing the LID design cost with an expected traditional design cost for each site. The case studies are located in many different regions of North America. The EPA study found that nearly all cost studies aggregate all material or all labor costs into large cost items rather than dividing or itemizing costs into individual LID elements within the watershed. Because of this, it is difficult to assign unit cost benefits based on individual LID practices.

Another challenge when analyzing costs studies is the lack of common baseline in which to compare different LID and traditional cost studies. Thus far, cost studies only address the capital savings from the construction of LID projects, such as a reduction in infrastructure, materials, and labor costs. Few studies assess the larger picture (life cycle) or potential benefits from LID concepts. This is mostly due to the uncertainty and difficulty of monetizing ancillary benefits of LID, such as the environmental benefits. The list below outlines points that should be included in future cost studies.

1) Potential increase of property values because of aesthetics, reduction in flooding, and so forth.

2) Savings by avoiding fines for failure of compliance with regulations (e.g., combined sewer overflow reduction).

3) Savings or additional costs associated with maintenance.

4) Savings by avoiding other potentially costly water quality treatment methods.

5) Savings from potential environmental benefits downstream.

6) Stormwater compliance credits.

7) Full life cycle costs.

Currently, the BMP Database includes cost data inputs. Cost data related to LID currently include a field to represent the "differential cost" of the site compared to traditional development. As LID concepts are added and finalized, some changes or additions may be made to include costs of LID practices.

It is recommended that the Water Environmental Research Foundation (WERF) Whole Life Cycle (WLC) cost models (Pomeroy et al. 2009, adjunct to Lampe et al. 2005) be used to document the whole life cycle cost of proposed BMPs in order to ensure the transparency of estimates for individual facilities. BMPs supported by the WLC model include:

- Retention Pond
- Extended Detention Basin
- Swale
- Permeable Pavement
- Green Roof
- Large Commercial Cistern
- Residential Rain Garden
- Curb-Contained Bioretention
- In-Curb Planter Vault

Users are encouraged to submit WERF WLC cost sheets with BMP Database study entries.

8.4 Conclusions

LID site monitoring introduces a variety of challenges and requires careful study design, documentation and implementation. It is recommended that study design be based on monitoring objectives, site specific conditions, budget, and desired accuracy. Generally a reference watershed approach is necessary to achieve monitoring objectives, and factors associated with the selected reference system are expected to heavily influence study design. Compared to conventional practice-scale monitoring, more thorough site characterization is recommended and additional instrumentation may be required to provide this characterization. Factors critical to LID site characterization include flow patterns, imperviousness characteristics, soil and groundwater conditions, watershed storage conditions, and water balance components. Composite characterization indices and metrics may be useful to quantify the extent of LID implementation and allow comparison between studies.

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Chapter 9

DATA INTERPRETATION AND PERFORMANCE EVALUATION OF LID MONITORING STUDIES

Low Impact Development (LID) is a stormwater management strategy that can be used to reduce runoff and pollutant loadings by managing runoff close to its source. Data obtained from LID monitoring studies can differ in important ways from data obtained in studies of conventional Best Management Practices (BMPs). Differences include:

- LID strategies tend to emphasize reduction in volume rather than reduction in concentration.
- The concept of an “influent” stream is not relevant in the context of a site-level study.
- Time scale of monitoring required to obtain representative data may be much longer than for a site-level LID study than a conventional study.

The careful interpretation and evaluation of data is critical in reaching appropriate conclusions about volume reduction and water quality benefits of LID. The purpose of this chapter is to recommend ways to interpret and evaluate hydrologic and water quality data obtained from LID monitoring studies to quantify the performance of the LID system, both absolutely and in comparison to conventional BMP implementations. This section first discusses volume reduction, which is perhaps the most important mechanism of LID and has important effects that carry through into water quality benefits and load reduction. This discussion considers both site-level studies and practice-level studies. Water quality benefits and load reductions are discussed primarily for LID site-level studies because the interpretation of water quality data from individual BMP studies is already considered in Chapter 7. Finally this section discusses ways of comparing volumetric and water quality performance of LID practices and sites to that of other BMPs.

9.1 Drawing Appropriate Conclusions Regarding Volume Reduction

Surface runoff volume reduction is an important component of the overall effectiveness of LID and BMP systems. Surface volume that is eliminated in BMPs does not directly discharge to the downstream drainage systems, reducing demand on system capacity and the hydraulic/sediment entrainment and transport impacts that increased runoff volumes may cause. In addition, reduction of surface runoff volume plays an important role in reduction in pollutant loadings to surface waters.

In general, LID monitoring studies attempt to answer one or more of the following questions regarding runoff volume reduction:

- How much runoff volume is reduced by a LID practice or a LID site on a long term average basis?

- How much runoff volume is reduced by a LID practice or a LID site under conditions specified for regulatory purposes (e.g. a specific design storm)?
- What affect does a LID practice or a LID site have on the frequency and timing of runoff leaving the site?
- How does a LID practice or a LID site impact the overall water balance of the site on a long term average basis? (i.e., How are deeper infiltration, evapotranspiration, and runoff balances changed?)

Because these questions generally relate to long-term hydrologic performance, and because hydrologic conditions at any given time are usually not average, volumetric data obtained from monitoring studied must be interpreted in the context of the hydrologic conditions preceding, during and following the study. Because monitoring studies are seldom conducted over a sufficiently long period to ensure average conditions have been documented, a major goal of data interpretation should be to appropriately extrapolate measured data to a broader context.

9.1.1 Data Recorded in the BMP Database

Exhibit 9-1 shows data fields recommended to be reported in BMP/LID studies and their relevance in interpreting volumetric results.

Exhibit 9-1. Recommended Reported Data and Relevance in Reaching Volume Reduction Conclusions

Reported Data	Currently Included?	Relevance in Volume Reduction Conclusions
Watershed Location	Yes	This permits analysis of precipitation patterns characteristic of the study location.
Watershed Area	Yes	This establishes total area tributary to monitoring point, coupled with precipitation depth and watershed rainfall-runoff characteristics. This represents the "inflow" to the system for site-level studies.
Watershed Imperviousness	Yes	This is an indicator of development density, related to quantity of runoff. It can be used as one of several factors to normalize runoff volume in comparisons between sites.
Predominant In-situ Surface and Near Surface Soil Types (developed condition)	Yes	This is an indicator of quantity of runoff in the monitored condition and is useful in understanding the importance of runoff, evapotranspiration, and deeper infiltration patterns from pervious areas of the watershed.
Reporting Period (Start and End Date/Time)	Yes	This establishes the time scale of the study, the season of year, and various corresponding factors (e.g., vegetation status, precipitation patterns, evapotranspiration rates, frozen ground).
Precipitation Start Time	Yes	This establishes the time of day for start of precipitation and various corresponding factors (e.g., fraction of average, seasonal, or monthly evapotranspiration, temperature).
Precipitation End Time	Yes	This establishes the duration of precipitation.
Precipitation Depth	Yes	This establishes the total input to system. When coupled with watershed area, this represents the "inflow" to the system for site-level studies. In above-ground practice-level studies, this represents the volume added directly to a practice.
Average Precipitation Intensity (Computed from Depth and Duration)	Yes	This is an indicator of the amount of runoff likely from pervious areas of the watershed and the average loading rate of pervious areas receiving run-on from impervious areas.
Antecedent Dry Period	Future	This is an indicator of antecedent watershed conditions and potential for dry weather pollutant build up.
Description of Antecedent	Future	A narrative description of conditions immediately prior to the start of monitoring, including key field notes,

Reported Data	Currently Included?	Relevance in Volume Reduction Conclusions
Watershed/Facility Conditions (narrative)		frozen ground conditions, facility storage available, high groundwater, etc.
Total Inflow Volume to BMP (Practice-level Only)	Yes	For practice-level studies, this provides precise quantification of discharge from watershed and inflow volume to LID practice.
Total Surface Discharge Volume (from BMP if Practice-level Study; from Watershed if Site-level Study)	Yes	This establishes the total discharge volume from monitored area, inclusive of the effects of LID practices in watershed and monitored LID practice (if present).
Observed or Estimated Drawdown Time of Total Storage from Brim Full	Yes	This establishes the time required to empty the facility and make storage available for subsequent storms. It is useful in efforts to calibrate models of the system or extrapolate limited datasets to long-term performance through rainfall analysis. This can apply to individual practices or, if designs are consistent amongst distributed controls, to multiple similar features.
Observed or Estimated Drawdown Time of Total Storage from Half Full	Yes	This provides information about the general pattern of the drawn down curve and enables a more robust use of study data.
Describe Key Weather Parameters During Study Period (narrative)	Future	Weather conditions can significantly affect the water balance of LID sites. Frozen soils can reduce infiltration rates; conversely, high ET can increase evapotranspiration rates. Characterization of ET, temperature and other similar factors are important in normalizing comparisons among LID sites.
Hydrologically Available Temporary Storage in Watershed (LID site level only as described in Section 8.2.4)	Future	This information helps to normalize the relationship between source areas and storage areas, both in terms of routing and relative volume for purposes of comparing LID sites. Tabular estimates of detained, retained and excess volume for a range of storm events are beneficial in developing these estimates. A PDF providing this information can be attached separately, or this information can be summarized narratively. Also provide units of measurement (e.g., acre-feet, watershed inches).
Storage Recovery Rate in Watershed (LID site-level only; described in Section 8.2.4)	Future	This describes the time for the LID site to recover hydrologically available temporary storage. Estimates of minimum, maximum and average recovery rates for retained and detained volumes should be provided.

9.1.2 Metrics for Interpreting Volumetric Results

The type of volumetric data obtainable and interpretation of these data differs substantially between practice-level studies and site-level studies:

- Practice-level studies: Practice-level studies are generally able to directly measure the total inflow to the facility and/or the total discharge from the facility. In the absence of a defined inflow, a surrogate such as precipitation depth, tributary area, and runoff coefficient may be used if the watershed is sufficiently well-defined (such as a roof-top or small parking lot). The intent of practice-level studies is to accurately quantify the volume reduction in a specific facility during a set of monitored storm events and, generally, to extrapolate these results to long-term hydrologic performance of that facility.

- Site-level studies: Site-level studies are generally able to measure the discharge from the system directly, but are not able to quantify the amount of surface runoff generated on-site and removed before reaching the outlet. Rather, the precipitation depth over the monitoring period represents the overall inflow to the system. The intent of site-level studies is to quantify hydrologic response during a set of monitored storm events, and generally, to extrapolate these results to long-term hydrologic response in comparison to other sites/watersheds.

Exhibit 9-2 provides a list of simple metrics than can be calculated for each event or monitoring period and analyzed in combination with storm characteristics or monitoring period total precipitation. These metrics are described individually in the paragraphs below.

Exhibit 9-2. Simple Metrics for Interpreting Single-Event Volumetric Data

Metric	Application
Presence/Absence of Discharge	Practice level and site level
Absolute Volume Reduction (In – Out)	Practice level only
Relative Volume Reduction (In – Out)/In	Practice level only
Discharge Volume per Area	Practice level and site level
Discharge Volume per Impervious Area	Practice level and site level

Care must be taken to avoid spurious correlations in the analysis of volumetric data. For example, it is convenient to correlate runoff coefficient to rainfall depth; however, because the runoff coefficient has rainfall volume as its denominator, a spurious correlation would be expected even if no genuine correlation existed.

Care must also be taken when averaging performance metrics from individual events. In some cases, an average may have relatively little utility in describing long term conditions. For example, the average of a ratio-based metric, such as relative volume reduction [(In –

Out)/In], would implicitly be biased towards events that occurred or were monitored most frequently rather than being weighted by event volume. Thus this average could not help provide an estimate of overall long term volume reduction performance. In other cases, averages may be more meaningful in theory, but limited by the representativeness of monitored events. For example the average of absolute volume reduction [In – Out] would only be expected to produce meaningful results if it was based on a monitoring period containing a representative distribution of inflow volumes.

The following methods are suggested for interpreting trends in volume reduction metrics:

- Scatter Plots
- Histograms
- Within-Storm Time Series

Examples of the use of scatter plots and histograms to visualize the simple metrics described above are provided in the sections below. For most studies entered into the BMP Database, time series data are not available. Therefore, the Within-Storm Time Series method is not discussed further in this document.

Presence/Absence of Discharge (Practice and Site Level)

Presence of discharge is a simple, informative metric that can be used to extrapolate the ability of systems to control the frequency of discharge. If a sufficient number of storms are monitored, data may be used directly to support conclusions regarding the threshold of discharge (e.g., the smallest storm to produce discharge was X, or the largest storm to produce no discharge was Y) or a probabilistic description of discharge (e.g., 90 percent of storms less than 1 inch produced measurable discharge, 50 percent of storms less than 0.7 inches produced no discharge). Such conclusions implicitly account for the various antecedent conditions encountered over the monitoring period. Given appropriate consideration for data representativeness and number of samples, these results can be used to make meaningful statements about the performance of the system. As some water quality criteria have an allowable exceedance frequency, information on the frequency of discharge can be important.

For site-level studies, there may be directly connected impervious areas (DCIA) downstream of the lowest LID feature but upstream of the monitoring location. This area would be expected to produce discharge in all but the smallest events; therefore the concept of a threshold of discharge may not always apply. In these cases, this method of interpretation may not yield meaningful results.

Histograms and probability plots can be effectively used to visualize frequency of discharge. Examples are shown in Exhibit 9-3. The bars on the chart represent the number of rainfall events and the number of runoff events, grouped into bins of rainfall depth. Bins are defined by their upper limit. For example, the bin labeled as 0.6 inches includes all events greater than 0.5 inches and less than or equal to (LTE) 0.6 inches. In the example below, 6 storm events fell into this bin and 4 of them produced runoff. The red dashed line plots the percentage of monitored events producing runoff in each bin.

Exhibit 9-3. Example Histogram of Frequency of Rainfall Events and Discharge Events for a Hypothetical Site-level Study

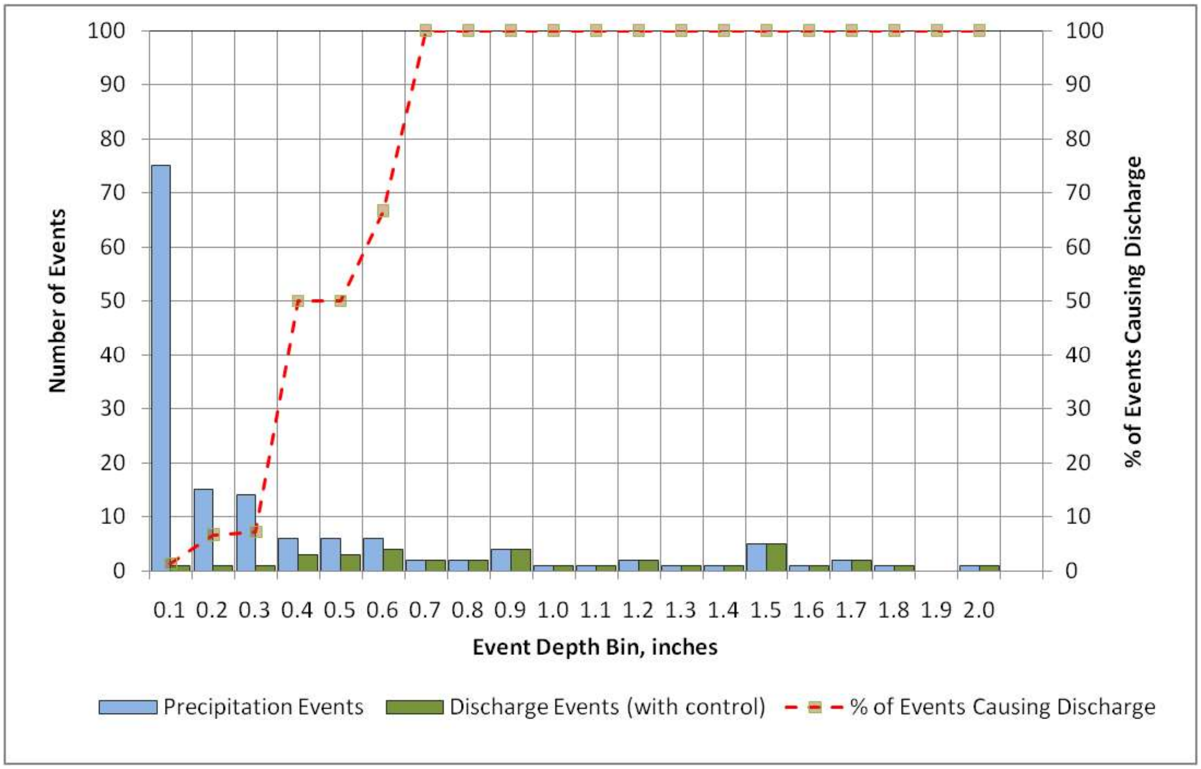


Exhibit 9-3 illustrates a way of visualizing the threshold of discharge from an example LID watershed as a function of depth. During the hypothetical monitoring period, no storm greater than 0.6 inches was completely retained, while at least minimal discharge occurred in one storm less than 0.1 inches. Likewise, during this monitoring period, three out of six events between 0.4 and 0.5 inches (bin labeled "0.5") caused discharge. Similar observations of this nature could be made from this chart.

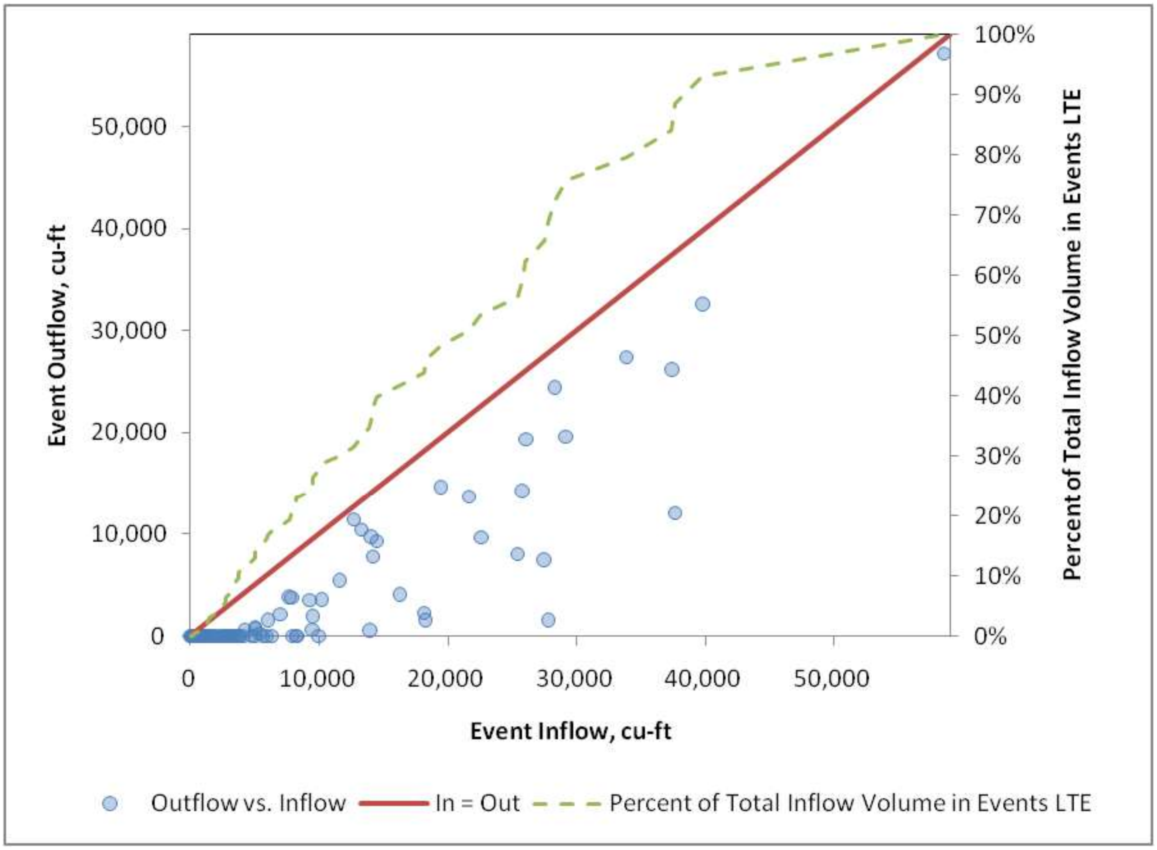
This method of analysis should not be used to estimate the cumulative volume reduction of the system, as the plot contains no data regarding the amount of volume reduced when discharge did occur.

Absolute Surface Runoff Volume Reduction (Practice Level only)

Absolute surface runoff volume reduction is simply the difference between inflow and outflow runoff volume for a specific monitoring event. This metric is informative in describing long-term hydrologic conditions if a sufficient number of events are monitored. To estimate long-term volume reduction, absolute volume reductions should be summed over a representative number of storm events and then divided by the total inflow volume to the facility over the same period of time. The method implicitly accounts for antecedent conditions, and would theoretically provide greater confidence in estimates as more data are added.

A scatter plot of event inflow versus outflow can be used to visualize the performance of the facility as a function of inflow volume (Exhibit 9-4). In this chart, blue circles represent individual event data. The "In=Out" line represents the performance that would be expected if no volume reduction or addition occurred in the practice. Points above this line would represent monitoring events with greater outflow than inflow, which could result from saturated antecedent conditions, high groundwater, and/or measurement errors. The dashed line represents the percentage of the total inflow volume occurring in events with inflow less than or equal to the X ordinate at each point.

Exhibit 9-4. Example Scatter Plot of Event Outflow Volume Versus Event Inflow Volume from a Hypothetical LID Practice-level Study

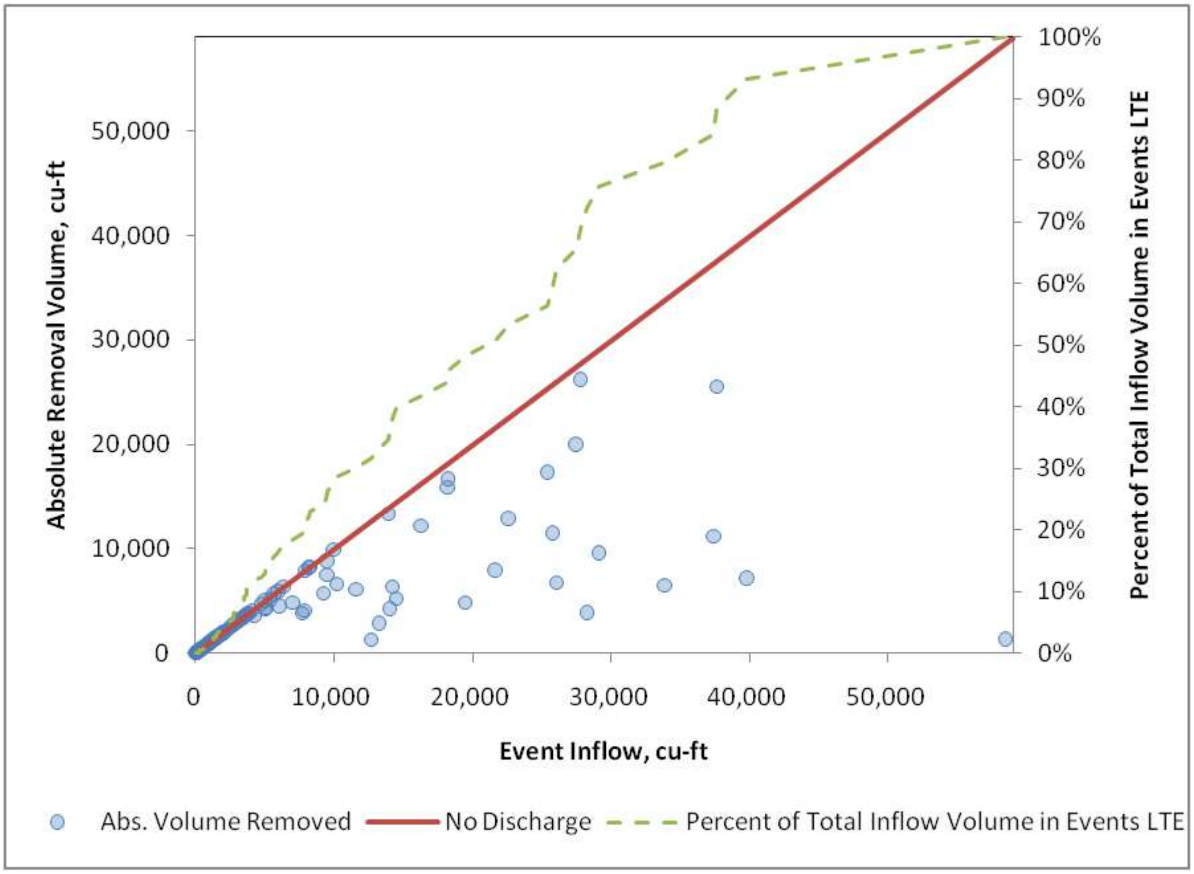


LTE = Less than or equal to (the X ordinate value)

Exhibit 9-4 illustrates the concept of a threshold inflow volume (in this case, approximately 6,000 cu-ft) below which discharge rarely occurs. It also illustrates a range (in this case, approximately 6,000 cu-ft to 30,000 cu-ft inflow volume) over which volume reduction ranges widely, from less than 5,000 cu-ft to more than 25,000 cu-ft. The variability over this range of inflow is explained by this range of inflow volume being similar to the storage volume of the LID practice. Low volume reductions could potentially be attributed to relatively short and intense storms following a previous storms (when the facility may be partly full), while higher volume reductions could potentially be attributed to longer, less intense storms occurring when the storage was at or near "empty" prior to the storm or where the inflow rates did not exceed infiltration rates or a combination.

Meaningful relationships can also be developed between absolute volume reduction and total inflow volume (see Exhibit 9-5). In this chart, the blue circles represent paired X-Y data, where the X ordinate is the inflow volume and the Y ordinate is the absolute volume reduction [In – Out]. The solid "No Discharge" line corresponds to the performance that would be expected if all inflow was removed from surface discharge in the practice. No points are expected to be above this line. For studies with data points showing measured outflow greater than measured inflow, negative Y values would be expected. The dashed line represents the percentage of the total inflow volume occurring in events with inflow less than or equal to the X ordinate at each point.

Exhibit 9-5. Example Scatter Plot of Event Absolute Volume Reduction Versus Event Inflow Volume from a Hypothetical LID Practice-level Study



LTE = Less than or equal to (the X ordinate value)

Exhibit 9-5 represents a different way of looking at the same data as Exhibit 9-4, and the same conclusions can be drawn regarding threshold of discharge and variability of volume reduction. Depending on the characteristics of the dataset, this method of visualization may better facilitate interpretation of these factors.

The cumulative percentage of inflow at each X ordinate relative to total inflow volume (dashed line) is informative in understanding the relative importance of different ranges of inflow volumes on overall performance. For example, storms that rarely result in surface discharge from the practice (<6,000 cu-ft inflow) account for approximately 20 percent of total precipitation volume. Storms in the range over which volume reductions vary greatly (6,000 to 30,000 cu-ft) account for approximately 50 percent of total precipitation volume. Storms in the range over which practices have little effect on discharge volume (>30,000 cu-ft inflow) account for the remaining 30 percent of rainfall volume in this example.

Relative Volume Reduction (Practice Level only)

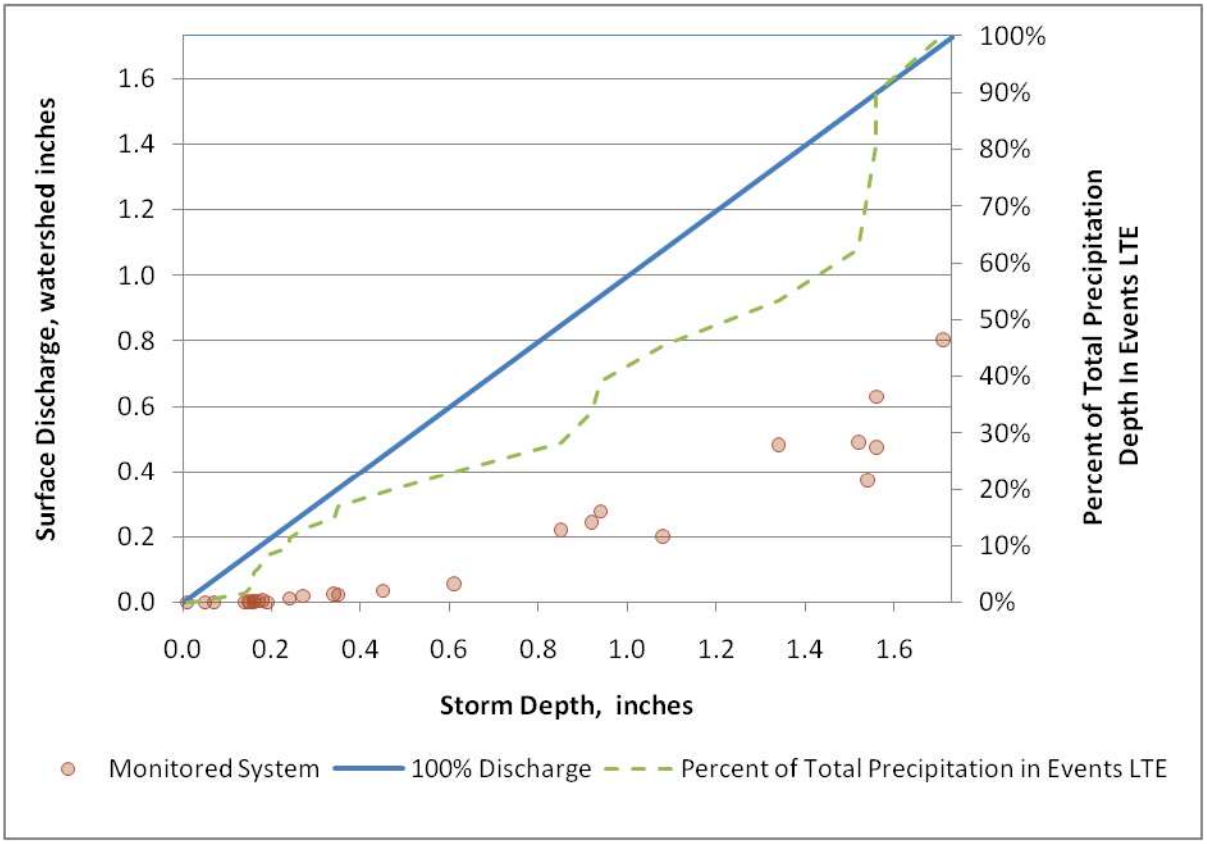
Relative volume reduction or "percent volume reduction" can be calculated for an individual storm as simply the difference between inflow and outflow divided by the inflow. This metric is informative for an individual storm event, but is prone to inappropriate interpretation if the results from individual storm events are simply averaged to yield an estimate of long-term volume reduction. For example, all storms less than the facility retention volume would be recorded as 100 percent volume reduction despite the range of storm depths this could include. Likewise large storms that cause significant discharge (i.e., low percent volume reduction) would only be recorded as one data point despite the fact that they may account for a much larger share of the total volume. Thus, this method of interpretation has limited use in extrapolation to broader conclusions.

Discharge Volume per Area (Site and Practice Level)

The discharge volume per area is calculated as the measured volume of discharge divided by the area of the tributary watershed. For one-to-one comparison to precipitation depth, this volume can be expresses as "watershed inches." The ratio of discharge volume to precipitation volume is typically referred to as the runoff coefficient; however it is expected that this runoff coefficient would be different for different size storm events and antecedent conditions. The trend of discharge volume per area with precipitation depth can be useful in extrapolating the long-term discharge volume from the system.

Similar to Exhibit 9-4, discharge volume per area can be plotted against rainfall to facilitate interpretation of hydrologic response. A hypothetical example is provided below (Exhibit 9-6). In this chart, red circles represent individual event data. The "100% Discharge" line represents the performance that would be expected if 100 percent of rainfall was converted to surface runoff. Values above this line would represent monitored events with greater outflow than inflow, which could result from saturated antecedent conditions, high groundwater, and/or measurement errors. The dashed line represents the percentage of the total precipitation occurring in events with precipitation depth less than or equal to the X ordinate at each point.

Exhibit 9-6. Example Plot of Discharge Volume per Areas Versus Storm Depth



LTE = Less than or equal to (the X ordinate value)

Exhibit 9-6 enables the visualization of several elements of hydrologic response expected to occur in LID sites level studies. First, for storm depths up to approximately 0.2 inches, no runoff occurs, representing the depression storage in the watershed [i.e., the threshold for runoff to occur, even from directly connected impervious areas (DCIA)]. From approximately 0.2 to 0.5 inches, the slope of the data is relatively shallow indicating that only a small portion of the watershed contributes to runoff, theoretically the portion of the watershed that is DCIA. Beyond the 0.5-inch storm, the slope of the data trends up again, signifying that a greater fraction of the watershed contributes to runoff in larger storms, likely as LID storage features become filled/infiltration rates are exceeded. While strong quantitative interpretations cannot be derived from this type of analysis, it is useful in order to gain a better understanding of hydrologic response of a watershed.

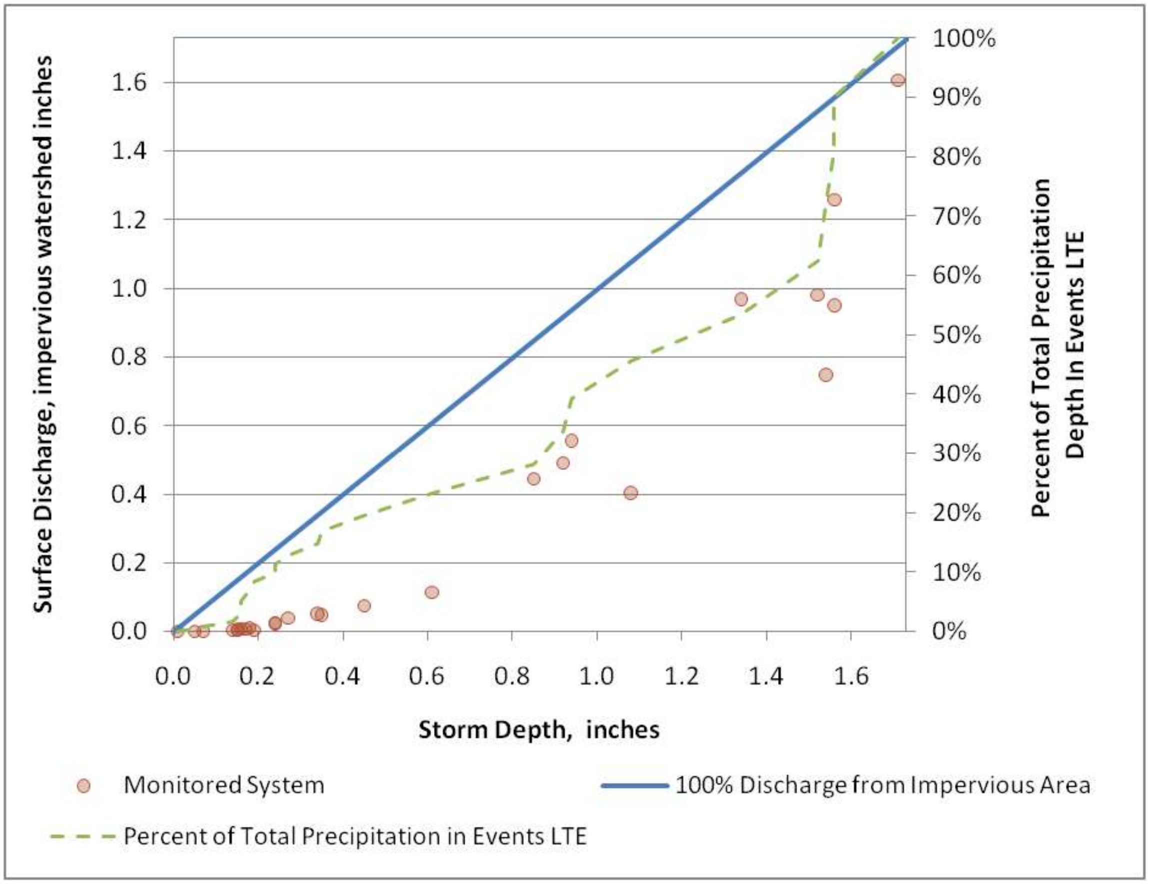
Discharge Volume per Impervious Area (Site and Practice Level)

The discharge volume per impervious area is similar to the discharge volume per total area described above, but is normalized to the impervious area of the watershed rather than the total watershed area. It is calculated as the measured volume of discharge divided by the total impervious area of the tributary watershed. The discharge volume can be expressed as "impervious watershed inches."

Normalization to impervious area has advantages and disadvantages. For ranges of storms for which runoff from pervious areas is negligible, this approach can be used to isolate and compare the effectiveness of LID practices on the site. For example, the effectiveness of LID practices to mitigate runoff could be compared between similar land uses with differences in imperviousness. All other factors being equal, the sites would be expected to discharge different volumes of water per total site area, but would be expected to discharge similar volumes of water per impervious area. However, this approach relies on the implicit assumption that runoff from pervious areas is negligible in both cases, which is not generally the case in larger storms or in the case of pervious areas with little interception storage and lower infiltration rates. Thus, this metric should be carefully applied.

The same example dataset used in Exhibit 9-6 is plotted as impervious watershed inches of runoff versus storm depth in Exhibit 9-7 below. The same trends are noted. In this chart, red circles represent individual event data. The "100% Discharge from Impervious Area" line represents the performance that would be expected if 100 percent of rainfall over impervious area was converted to surface runoff and no runoff occurred from pervious areas. The dashed line represents the percentage of the total precipitation occurring in events with precipitation depth less than or equal to the X ordinate at each point.

Exhibit 9-7. Example Scatter Plot of Discharge Volume per Impervious Area Versus Storm Depth



LTE = Less than or equal to (the X ordinate value)

9.1.3 Consideration of Measurement Error in Interpretation Methods

In interpreting volumetric data, consideration should be given for the precision and accuracy of system inflow and outflow volume measurements. Random measurement errors associated with the resolution of monitoring equipment can be magnified in the evaluation of volume reductions, particularly for practices that achieve relatively little volume reduction, or for which limited number of data points are available. For example, if inflow volume measurements have a precision of +/- 10 percent and outflow measurements have the same precision, the calculated variability in volume reduction may be more a function of uncertainty in measurements than in the performance of the practice, unless the volume reduction is fairly large. The impacts of measurement precision on conclusions can be reduced by using methods that aggregate long-term inflow and outflow volumes (e.g., comparison of total inflow to total outflow volume, or total rainfall to total site discharge). Methods of interpretation that rely on the visualization of individual event data are inherently sensitive to measurement errors. However, recognition of the potential for errors (and the potential magnitude of those errors) as well as larger sample sizes can improve the strength of conclusions drawn from these observations. Note that analysis of relative volume reduction or "percent volume reduction" on a storm-by-storm basis is especially sensitive to the effects of measurement precision.

The accuracy of volumetric measurement can be diminished by a variety of factors, including improper calibration of equipment and omission of any important factors. Accounting for all inflows and outflows to/from the system is of particular importance in volume reduction studies. Some types of unmeasured volumes may include: volume of direct precipitation on the practice; volume of groundwater seepage into the practice; volume evapotranspirated; other volumes which are not reflected in inflow and outflow volumes measured at discrete monitoring points. These volumes should be estimated where possible and factored into event totals and/or long-term totals as appropriate to prevent inaccuracies in volumetric measurement.

9.1.4 Comparing Performance to Design Objectives and Criteria

Often, an underlying goal of monitoring is to compare LID practice and site performance to prior design objectives or performance criteria. Design objectives and performance criteria applicable to LID practices and sites can take a number of forms. Most commonly LID practices are designed to capture the runoff from a specific design storm or intensity. Capture may include retaining water on site via infiltration, evapotranspiration or reuse, or detaining and discharging treated water. In either case, the time over which storage capacity should be recovered (i.e. the time it takes the facility to empty) is usually specified as an accompanying design objective.

LID practices may also be designed with the direct intent of capturing a specified percentage of average annual (i.e., long term) runoff or reducing discharge volume to a specified level on a long-term basis.[1] In this case, design criteria are typically developed through analysis of precipitation records using continuous hydrologic simulation. Methods of sizing may implicitly or explicitly incorporate the emptying time of the facility (i.e. the time it takes to recover storage capacity for subsequent storms). For example, long-term hydrologic simulation might show that a design volume of 0.8 watershed inches would be required to capture 80 percent of average annual runoff if a bioretention practice was designed to empty in 36 hours, while a design volume of only 0.5 watershed inches might be required if the same facility was designed to empty in 18 hours.

The design objective or performance criteria applicable to the study provides guidance for how volumetric performance data should be evaluated. In the first case described above (design storm-based objective), relatively few monitored events may be necessary to confirm that the facility is meeting its performance objectives (performance under a given design condition). For example, the design objectives of the facility could be evaluated by monitoring and analyzing data from a subset of events similar to the design event, with a range of antecedent conditions, and monitoring the emptying times of the facility under different seasonal conditions. If overall monitored performance is reasonably consistent with

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[1] A typical goal is to match the "pre-development" discharge volume, however it is noted that matching overall discharge volumes does not necessarily ensure matching of pre-development peak discharge rates, frequencies or durations, or overall water balance.

design objectives, it can be reasonably concluded that the facility meets the design objectives and the performance criteria implied by those objectives.

However, this is not likely a common case. If the design objectives are not confirmed through comparison of design storm performance to design storm objectives, if performance criteria are based on long-term performance, or if study objectives include the explicit quantification of long-term performance, the study must either continue for a long period of time or other methods must be employed to extrapolate the performance of the system.

In the case of LID sites, specific design objectives, such as design storm methods, are less common than for specific LID practices, thus it is more common that extrapolation of long-term performance will be required to meet study objectives.

Extrapolating Study Results to Long-Term Volume Reduction Performance

Extrapolating a limited monitoring dataset to long-term volume reduction performance may be critical in meeting study objectives and evaluating LID practice or site performance against established criteria. The following are two common ways of extrapolating these results:

1) Precipitation analysis: Monitoring datasets may permit the development of average relationships between precipitation and system performance. These relationships could potentially be probabilistic in nature. For example, the average discharge volume in events between 0.4 and 0.5 inches is 32,400 cu-ft and the standard deviation is 15,500 cu-ft. If similar relationships could be developed for each rainfall "bin", a statistical sampling routine could be implemented in combination with storm events extracted from long-term rainfall records to estimate total discharge. Alternatively, a moving average of response could be developed and applied directly to each event. For example, a moving average of watershed discharge per area versus event depth could be applied to a long-term cumulative distribution of storm depths to estimate total long-term discharge. The critical element of this approach lies in the strength of the relationships that can be developed between precipitation records and practice performance or site responses.

2) Continuous Simulation Models: These models represent a potentially valuable tool for extrapolating a relatively small number of monitored events to long-term performance. Guidance on effective and appropriate use of models is beyond the scope of this Manual, however the user should consider data needed to calibrate and validate hydrologic models in developing a study design. Hydrologic models can facilitate highly detailed analysis of system performance over a long time scale. Critical to this approach is minimizing model-induced errors and using a model within the limits of its applicability.

9.2 Water Quality Benefits and Load Reduction

Water quality benefits and load reductions from LID practices and sites are a function of both water quality treatment functions and volume reductions provided by LID practices. Methods of interpretation of water quality benefits of practice-level studies should be consistent with methods described in Chapter 1 through 7 of this Manual and are not described in this chapter. Likewise, methods for analysis of event mean concentrations and pollutant loadings at a discrete monitoring station are described in Chapter 7 of this Manual and are not described in this chapter.

Description of the water quality benefits and load reductions achieved by LID sites should account for the pollutant loads removed through treatment in the LID practices on site as well as pollutant load reduction achieved via volume reduction. To quantify these components directly would require estimation of the quality and quantity of runoff prior to entering a LID practice, as well as the runoff avoided or increased through LID site design practices. Clearly, measuring pollutant removal from LID sites directly will not generally be feasible. Of greater interest is how water quality benefits and load reductions should be interpreted from before/after or control/impact studies.

9.2.1 Interpreting Water Quality Benefits of LID Sites through Reference Watershed Studies

LID sites can have water quality benefits over uncontrolled development sites by reducing the frequency of discharge, reducing the average concentration of discharge, reducing pollutant loads, or by all three. When comparing to a reference condition (either a pre-retrofit condition or control condition), an attempt should be made to quantify each of these potential benefits.

Reduction in frequency of discharge is a strictly volume-based phenomenon that can be interpreted as described in Section 9.1. It may also be of interest to compare frequency of discharge from the monitored site to pre-development frequency of discharge if these data can be estimated from local hydrologic observation or model results.

Concentration of discharge can be interpreted as an average long-term discharge volume (i.e., the average event mean concentration) or as a distribution of event mean concentrations. For example, it may be of interest to know how frequently the concentration of a given pollutant exceeded a concentration-based water quality standard. In comparing such results between a LID and control watershed, it is important to consider the potential for fewer discharge events from the LID watershed, thus for appropriate comparison, a common normalizing variable should be used. In this case, expressing exceedance of a water quality threshold as a count per year would be more appropriate than expressing it as a percentage of total discharge events. It is also important to consider that concentration reductions may not be expected in sites that achieve significant volume reduction. For example, an increase in concentration of some pollutants might be expected from a site that has volume reduction practices applied to relatively “cleaner” land uses, but less volume reduction on relatively “dirtier” land uses. A larger fraction of the discharge water in the controlled condition would originate from the “dirtier” land use, thus potentially increasing the concentration. In this case, a reduction in loads would still be expected.

Estimates of load reduction should carefully consider the non-linearity of runoff response that is characteristic of LID watersheds (i.e., a few large storms can dominate overall discharge volume) and the potential for concentrations of some constituents to be greater in more intense storms. A comparison of total loading over a representative period of record is the most appropriate way to compare study and reference watersheds. If possible, individual event mean concentrations (EMCs) should be multiplied by individual event discharge volumes to compute event loads. While average EMCs of discharge should be applied with caution when computing total pollutant loads, they may be useful in estimating the loading over a monitoring period if not all storms were sampled but the discharge volumes from all the storms were monitored. In this case, the average of EMCs could be applied to the volume that was not sampled in the study. Care should be taken to avoid the interpretation of volume and/or load reductions based on results from a non-representative period of record. For example, if only small storms were monitored, the benefits of an LID site could be drastically over-predicted, and vice versa.

9.2.2 Potential Groundwater Impacts

LID systems tend to emphasize infiltration and thus have the potential to impact groundwater quality and quantity. If subsurface monitoring is conducted, it will be necessary to interpret these data to describe potential groundwater impacts. Subsurface water quality monitoring studies should attempt to describe:

- Presence or absence of flow of infiltrated water to groundwater and frequency patterns of presence of discharge (i.e., seasonal, wet year vs. dry year)
- Increases in groundwater levels and/or downgradient surface discharges (shallow groundwater discharges)
- Average long-term concentration of infiltrated water reaching groundwater
- Average long-term annual loading of pollutants to groundwater
- Patterns of concentration and loading of infiltrated water reaching groundwater
- Long term trends in concentration and loading with time

Fundamentally, subsurface data may be interpreted in the same way as surface water quality and volumetric data. Representative conditions must be monitored to support direct conclusions about long-term average water levels, concentrations, and loading. Ideally, loading over a monitoring period would be calculated from incremental periods of flow and the average concentration over those periods. Error may be introduced if total discharge volume is multiplied by average concentration.

Modeling may help extrapolate limited monitoring periods to long-term averages and patterns.

9.3 Comparison of LID to other BMPs

LID practices in themselves are not fundamentally different from many other BMPs and their performance can be interpreted and described identically. Most commonly, performance should be described as a probabilistic description of influent and effluent quality, average load reduction, and/or average volume reduction. Studies with comparable tributary watersheds and comparable study design may facilitate further comparisons such as frequency of discharge, frequency distribution of concentration, and temporal pattern of loading.

One major difference between LID practices and conventional BMPs is the typical dependency of LID practices on volume reduction. Fundamentally, volume reduction processes can be considered within the framework of a normalized storage volume and a storage recovery rate, regardless of BMP type or scale. While magnitudes of storage and recovery rates vary between LID sites, LID practices, and conventional BMPs, this overall framework provides a basis for comparison between studies in the same category, as well as across categories. A comparison of normalized storage volumes and recovery rates between sites can be used to help interpret or predict differences in performance. As described in Section 8.2.4, spatially linking tributary areas to storage volumes and recovery rates provides a stronger basis for comparison between sites in which storage is distributed differently (i.e., evenly distributed storage volume versus lumped or unevenly distributed storage volume).

Because LID practices and sites typically depend on volume reduction, LID practices often do not discharge “treated” water. Instead, everything that is captured is retained and only the overflow or bypass is discharged. Therefore a comparison of average discharge concentration between a conventional BMP that treats and releases water back to the surface and a LID practice that only discharges bypass or overflow may not provide a representative description of overall performance. While it is important to recognize that volume reduction-based LID practices could indeed result in higher average discharge concentrations than conventional treat-and-release BMPs, the total load discharged from the system and the load removed in the practice or BMP provides a better basis for comparison of overall performance.

While LID site-level studies are notably different than individual LID practices level studies and conventional BMP studies, comparison between these systems is still possible. LID studies attempt to provide a long term description of discharge water quality and discharge loads, which are both comparable to conventional BMP studies. Likewise, LID site-level studies attempt to quantify the volume of runoff mitigated by the composite suite of LID practices, which is also comparable to conventional BMP studies. Finally, LID site scale studies attempt to quantify the frequency of discharge and threshold conditions for discharge to occur. While conventional BMPs may or may not include mechanism to change the frequency of discharge, the frequency/timing of discharge is a fundamental factor in receiving water protection and is a valid basis for comparison even if other BMPs do not have measureable benefits.

9.4 Conclusions

Appropriate methods of data interpretation are necessary to support valid comparisons between different practices and sites. The emphasis on volume reduction that is inherent in LID principles requires that appropriate conclusions about volume reduction are made from monitoring studies. Methods of interpretation of volumetric data that can be readily extrapolated to long term performance are preferred. Because LID practices and sites are expected to perform differently under different storm magnitudes, methods that do not factor in event magnitudes are discouraged. Visual observation of data as scatter plots, histograms, and cumulative density functions is recommended as it allows interpretations of hydrologic response that may not be as apparent in statistical summaries. LID practices and sites can be compared to conventional studies on the basis of discharge frequency, discharge volumes, and distributions of concentrations and loads.

9.5 References

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Chapter 10
LID MONITORING CASE STUDIES

Low Impact Development (LID) is a stormwater management strategy that can be used to reduce runoff and pollutant loadings by managing runoff close to its source. Chapter 8 of this Manual describes LID monitoring philosophy, study design, data acquisition, and reporting methods. Information about how to interpret and evaluate LID monitoring data is included in Chapter 9. The primary focus of these previous two chapters is on site level (or watershed scale) LID studies. This chapter presents and summarizes four case studies of site level LID monitoring projects that provide insight into methods potentially applicable to future monitoring projects. The four sites include:

1) Cross Plains, WI
2) Burnsville, MN
3) Jordan Cove, CT
4) Somerset, MD

All four studies use a Reference/Paired Watershed approach (Clausen and Spooner 1993), also known as the Before-After/Control Impact (BACI) study method. These case studies were chosen as examples because they each differ slightly, while together they cover a number of different stages of LID. Exhibit 10-1 summarizes the major monitoring design components for a quick comparison between each of the four case studies.

Exhibit 10-1. Case Studies Summary

Case Study	Flow Data resolution [mins]	# of rain gages	# of flow locations	Automated Samples?	Grab Samples	Organics / Nutrient Samples?	Metal Samples?	Other Measured parameters?
Cross Plains, WI								
Control (Traditional)	1	1	1	Y	Y	Y	N	Y
Treatment (LID)	1	1	3	Y	Y	Y	N	Y
Burnsville, MN								
Control (Traditional)	5	-	1	N	N	N	N	N
Treatment (LID)	5	1	1	N	N	N	N	N
Jordan Cove, CN								
Control #1 (Traditional)	NR	-	1	Y	Y	Y	Y	Y
Control #2 (Traditional)	NR	-	1	Y	Y	Y	Y	Y
Treatment (LID)	NR	1	1	Y	Y	Y	Y	Y
Somerset, MD								
Control (Traditional)	2	1	1	Y	N	Y	Y	N
Treatment (LID)	2	-	1	Y	N	Y	Y	N

NR – Not reported

10.1 Cross Plains, WI

The Cross Plains LID monitoring study was performed by the U.S. Geological Survey (USGS) in cooperation with Wisconsin Department of Natural Resources. This study compared a residential subdivision using LID techniques to one using a more conventional, fully connected stormwater conveyance system. The objectives of the study were to determine whether using LID techniques in a residential subdivision improved the quality of the stormwater runoff and/or reduced the runoff volume compared to the more traditional approaches.

The Cross Plains study used a paired or reference watershed approach. Two watersheds were monitored: one with a conventional stormwater system built in the early 90s; and the other with LID stormwater concepts. The conventional watershed had the following characteristics: curbs; gutters; a storm sewer discharging to a detention basin; larger street widths (40 ft); and a mix of single dwellings and commercial land. The LID watershed contained the following characteristics: LID stormwater conveyance; grass swales; small detention followed by a large infiltration basin; an infiltration trench; more open area; single dwellings; and narrow street widths (32 ft). Exhibit 10-2 shows the LID (left) and the traditional (right) watersheds.

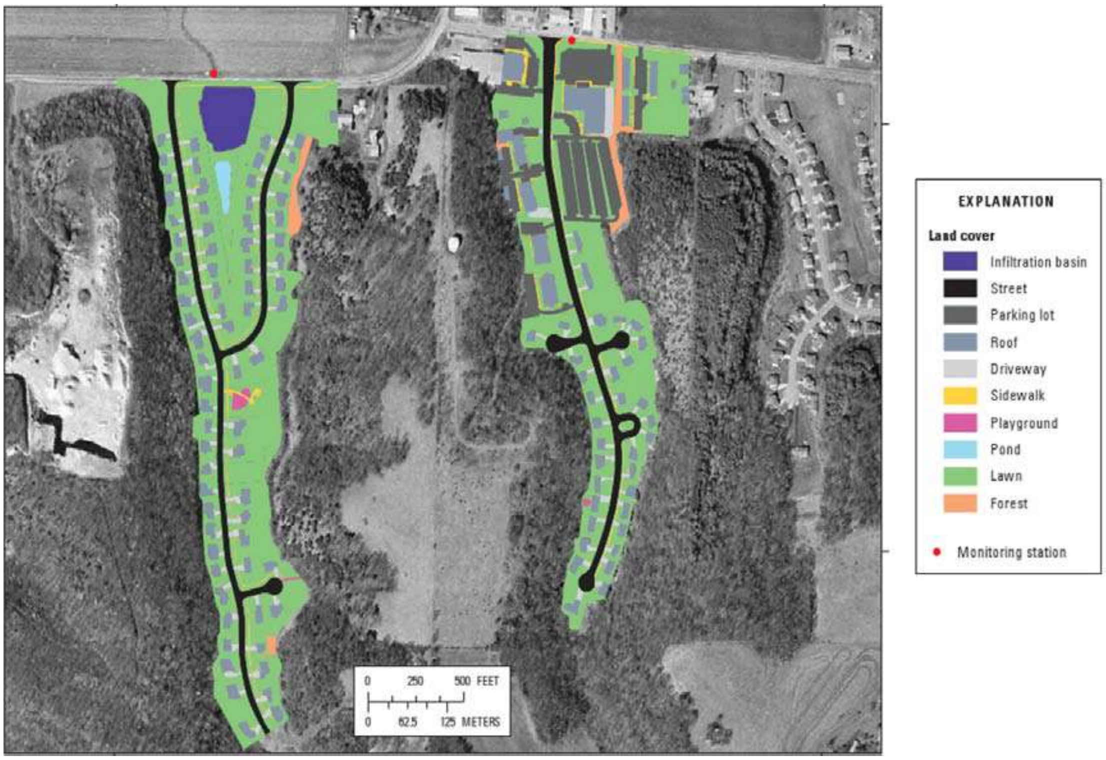


Exhibit 10-2. Aerial View of a LID Site and a Traditional Watershed (Selbig and Bannerman 2008)

This study shows a relatively intensive monitoring plan, as indicated by the two additional flow measurement locations located in the LID watershed. These two additional flow measurement locations were positioned at the end of the grass swale emptying into the small detention basin and at the entrance of the infiltration basin or outlet of the detention basin. Water quality sampling was not performed at these two stations.

Sampling was performed at the outlets of both catchments. For each sampling event, volume weighted sampling started once a specific water depth (0.1 to 0.15 ft) at the weir was reached, and continued to resample once a given volumetric threshold was calculated using one minute monitored flow increments.

Results from the study show that the LID catchment reduced the frequency of discharge, runoff volume and peak flows for most storms. The LID watershed produced measureable discharge in only six events with precipitation depth less than 0.4 inches, while the conventional watershed produced discharge in 180 events with precipitation depth less than 0.4 inches. The conventional catchment produced between 1.3 and 9.2 times more discharge than the LID catchment on an annual basis over the 6 years monitored.

The authors of the study noted that "with large storms and saturated soils, the ability of low-impact design techniques to reduce runoff, and thus constituent loads, can be greatly diminished" (Selbig and Bannerman 2008). In two years of the 6-year study, the LID watershed discharged greater loads of total solids, total suspended solids, and total phosphorus than the conventional catchment, with the majority of discharge loads from the LID basin associated with infrequent large events.

For more information, see the USGS document by Selbig and Bannerman (2008).

10.2 Burnsville, MN

The Burnsville monitoring study is an example of a simple LID monitoring study as it contains only two flow monitoring stations at which no samples were collected. The study purely focused on the volume and peak flow reduction of LID practices.

The rain garden retrofit and monitoring project in Burnsville, MN used a reference watershed approach. Two catchments with similar characteristics were evaluated during two monitoring periods. Exhibit 10-3 shows a plan view of the treated catchment.

Exhibit 10-3. Burnsville Rain Garden Treatment Area (Barr Engineering 2006)

The monitoring focused primarily on the flow out of the bottom of the watershed. The first period of monitoring was a calibration period that lasted nearly two years. This calibration period included no treatment in either catchment and was conducted simply to obtain a paired data set with which to statistically compare the responses of the two watersheds. Exhibit 10-4 shows the results of paired event runoff volumes from the two watersheds during the calibration period, both without control.

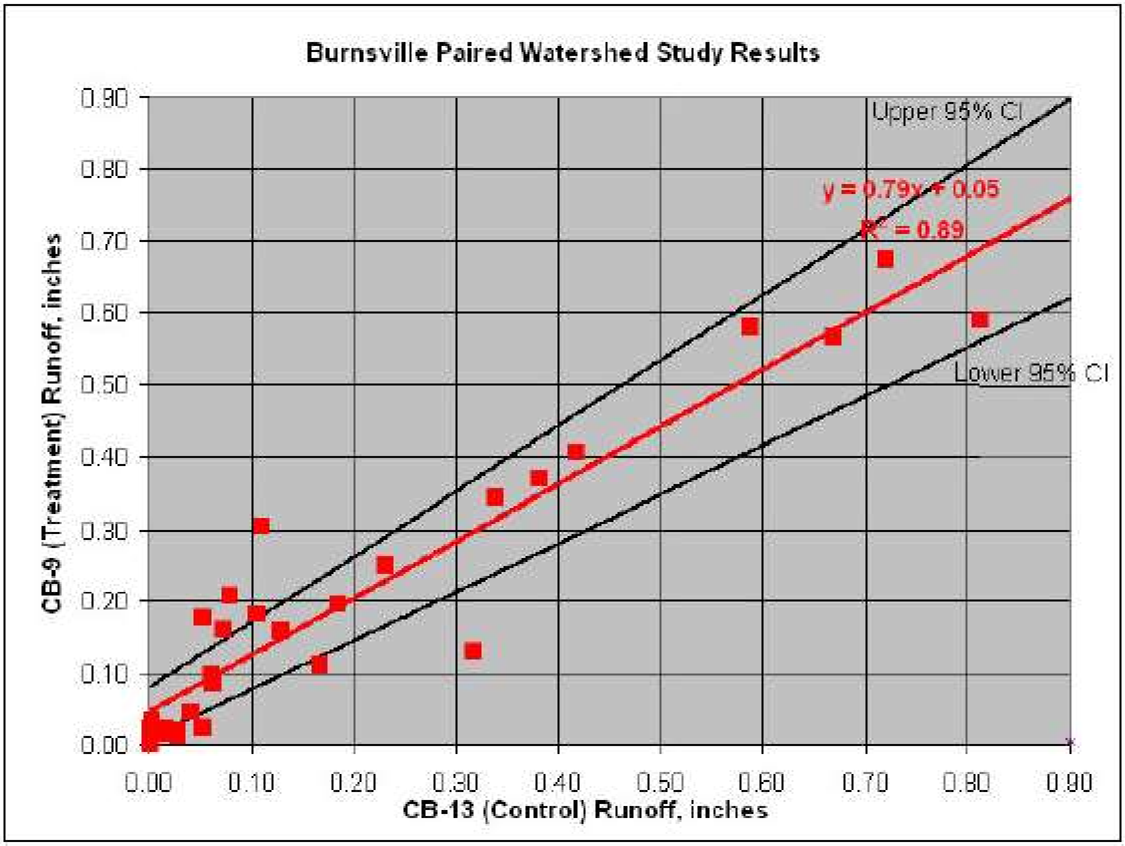
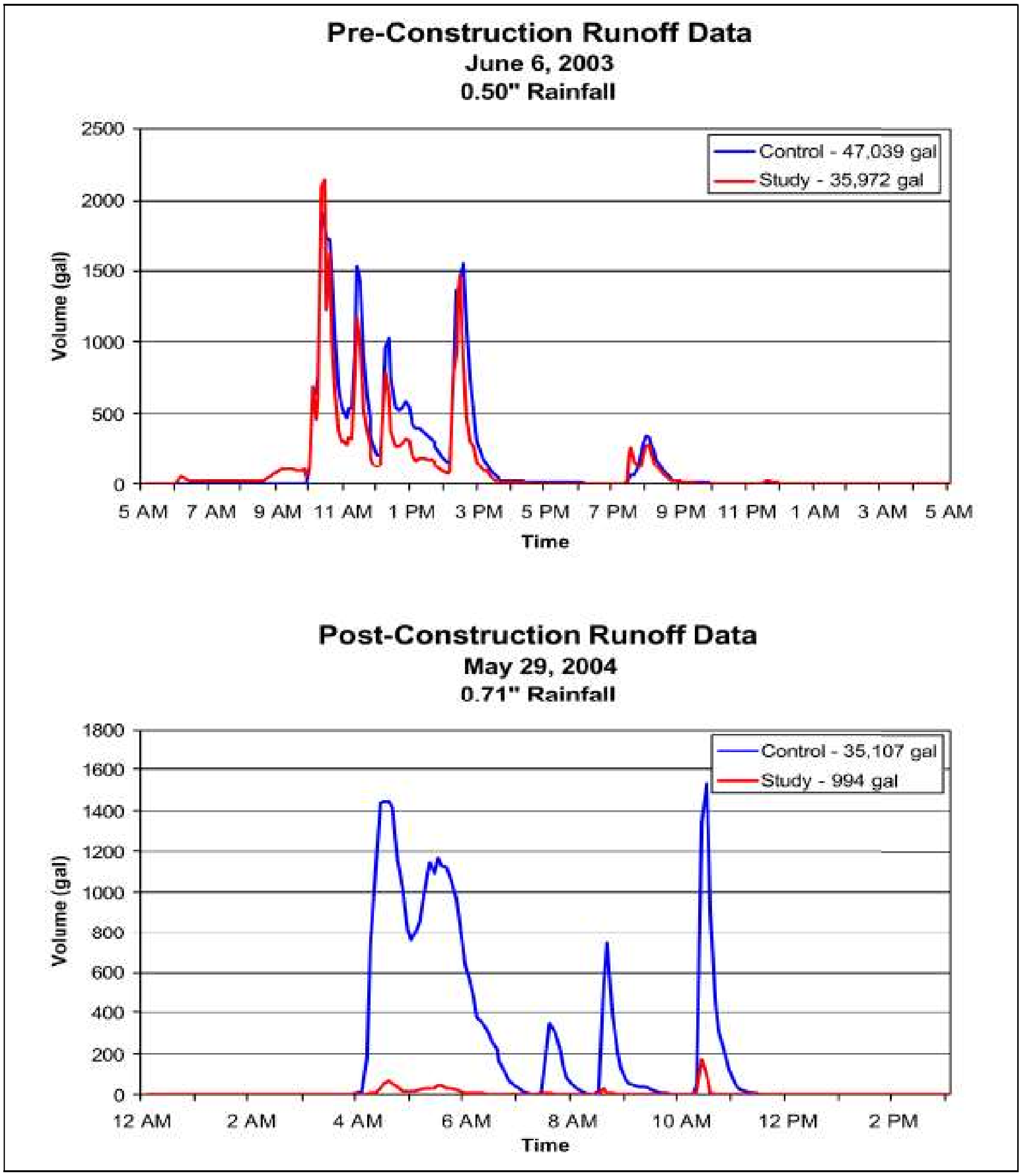


Exhibit 10-4. Scatter Plot of Paired Runoff Volumes from the Control and Treatment Watersheds, before Treatment Was Applied (Barr Engineering 2006)

Results showed consistently lower runoff from the treatment catchment (prior to retrofit), which was factored into eventual conclusions.

A second monitoring period, the treatment period, lasted approximately one and one-half years. During the treatment period, one catchment was being treated and one remained unchanged. The treatment catchment is termed "treatment" because 17 rain gardens were installed after the end of the calibration period. The rain gardens were placed in the front yard adjacent to the streets, and in the backyard.

The results show that the 17 rain gardens had a marked effect on reducing the runoff from the treatment catchment compared to the untreated site for the same storm events. It was reported that the cumulative effect of the 17 rain gardens reduced runoff volumes by as much as 90 percent (Barr Engineering 2006). An example storm response is shown in Exhibit 10-5, and the plot of discharge per area post-retrofit is displayed in Exhibit 10-6.



Pre-Construction Runoff Data
June 6, 2003
0.50" Rainfall

Post-Construction Runoff Data
May 29, 2004
0.71" Rainfall

Exhibit 10-5. Pre- and Post-Construction Runoff Data at Control and Test Watersheds
(Barr Engineering 2006)

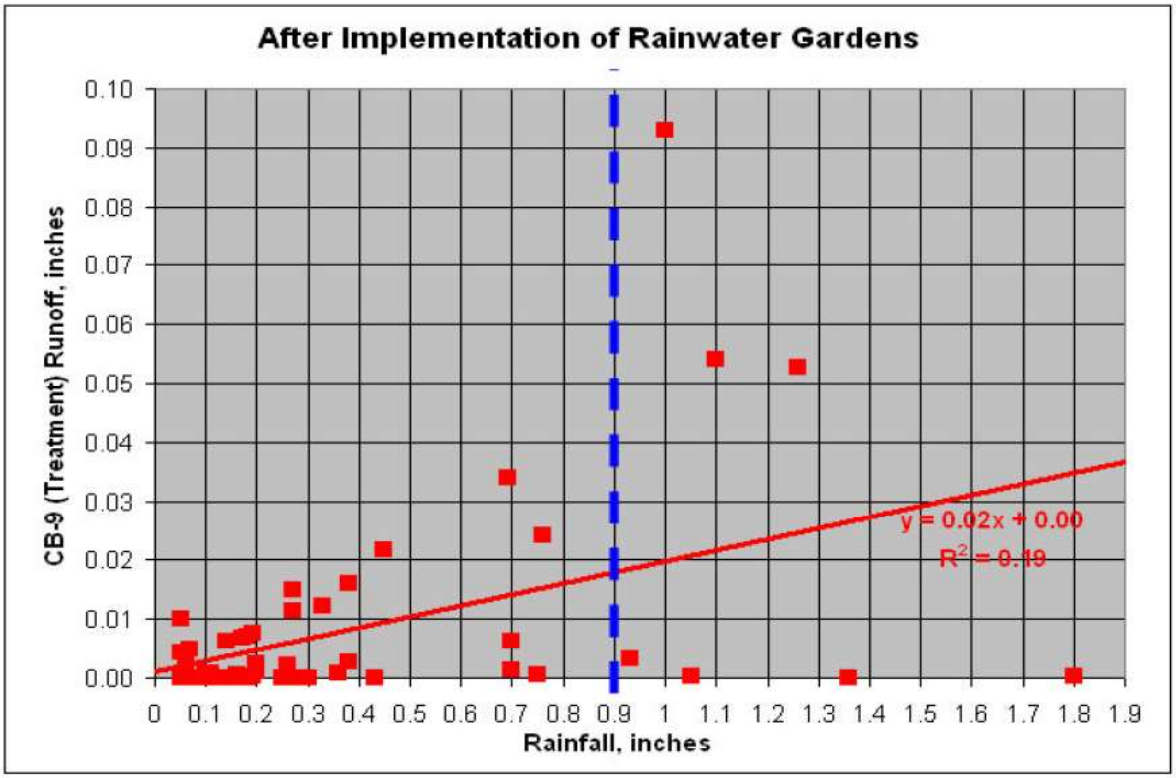


Exhibit 10-6. Scatter Plot of Discharge Volume per Area Versus Rainfall after Retrofit
(Barr Engineering 2006)

Exhibit 10-6 demonstrates consistently effective control of discharge volume, particularly below the design depth of the retrofit rainwater gardens (0.9 inch). As discussed in Chapter 9, a scatter plot method of interpretation enables an assessment of the variability of performance (typically cause by antecedent conditions and storm shape) with storm depth, as well as general conclusions about performance. It is interesting to note that a storm as large as 1.8 inches produced no runoff from the site, while a storm as small as 0.05 inches produced measureable runoff.

10.3 Jordan Cove, CT

Similar to the two case studies above, the Jordan Cove monitoring project also used a reference watershed approach. In this study, funded largely by the EPA and the Connecticut Environmental Protection Department, three catchments were monitored to study the effects of different types of development and compare traditional methods to the LID approach. The three catchments included: (1) a control catchment, which did not change during any time of the monitoring period; (2) a traditional catchment, which used traditional stormwater design (e.g., curbs, gutters, and sewers) and was constructed during the monitoring period; and (3) a LID catchment that used stormwater concepts, such as bioswales, open areas, clustered house layout, bioretention cells and permeable pavements, and was constructed during the monitoring period. Examples of LID practices installed on this site are shown in Exhibits 10-7 and 10-8.

Exhibit 10-7. Jordan Cove Bioswale (UCONN, 2007)

Exhibit 10-8. Jordan Cove Permeable Pavement (UCONN, 2007)

The monitoring schedule was partitioned into three periods: (1) Calibration, during which no changes occurred; (2) Construction, during which one traditional watershed was developed along with the LID catchment; and (3) Post-construction. This phased plan facilitated the study of the changing effects on water quality and runoff quantity throughout the entire development process.

Monitoring consisted of flow measurements and samples collected at the outlet of each catchment. Samples were collected for each 500 ft^3 of runoff. The water quality parameters monitored were total suspended solids, total phosphorus, total Kjeldahl-N, ammonia-N, nitrate+nitrite-N, fecal coliform, biological oxygen demand, copper, zinc, and lead. In addition to the watershed monitoring at the outlets, various ancillary studies were performed to analyze how the lot properties in the LID catchment influenced water quality and runoff. For example, three studies performed on the LID catchment include: (1) Driveway runoff study; (2) Lawn nutrient study; and (3) Household surveys. Cost estimates for the various items built in the traditional and LID catchment were also documented.

Conclusions made by this study included:

1) Post-development peak flow rates and runoff volumes can be equal to those of predevelopment by using LID concepts for the events monitored.

2) Post-development total suspended solids (TSS) levels were greater than predevelopment levels

3) Nitrogen and phosphorus exports were reduced below the project goal of 65 percent and 40 percent, respectively. However, bacterial export was not reduced to the goal of 85 percent. (Note: Percent removals are not advised as measures of performance by the authors of this guidance Manual.)

10.4 Somerset, MD

During the Somerset monitoring project, Cheng et al. (2003) also used a reference watershed approach to analyze the differences in hydrologic performance between a traditional development and a LID development. Exhibit 10-9 shows an aerial view of the project site and the location of the two monitoring stations. The LID catchment contained grass swales, a disconnected impervious area, and bioretention practices. The conventional watershed contained a typical stormwater system of curbs, gutters, and a storm pipe system. Both watersheds were monitored with a single rain gage, two stream gages, and two automatic water quality samplers.

Exhibit 10-9. Somerset Monitored Watershed (Cheng et al. 2003)

The monitoring stations were programmed to measure flow at two minute increments and collect samples at every 250 ft^3 of the volume for small events and at every 500 ft^3 of volume for large events. This volume-weighted procedure produced an event mean concentration for each storm event. The samples were tested for the following constituents: lead, zinc, copper, total nitrogen, total phosphorus, and TSS. Overall, most annual loads were reduced at the LID site compared to the conventionally developed watershed, while total nitrogen remained the same and total phosphorus loading increased. Additionally, fewer events that produced runoff occurred at the LID site than the conventionally-developed watershed and fewer events with peak flow greater than 0.1 cfs/acre were produced (Exhibit 10-10).

Exhibit 10-11 shows that the effectiveness of the LID watershed is greatly reduced after available temporary storage is filled. While the initial peak in the monitored storm resulted in a significantly lower peak flow than in the conventional watershed, subsequent intra-storm peak intensities actually resulted in greater peak runoff than from the conventional watershed. This is similar to the observation by Selbig and Bannerman (2008) that the effectiveness of LID practices "can be greatly reduced" in saturated conditions. Nonetheless, the study still found a reduction in surface discharge of approximately 40 percent compared to the conventional site over the period of record, reflecting the importance of smaller, more frequent storms in long-term cumulative hydrologic response.

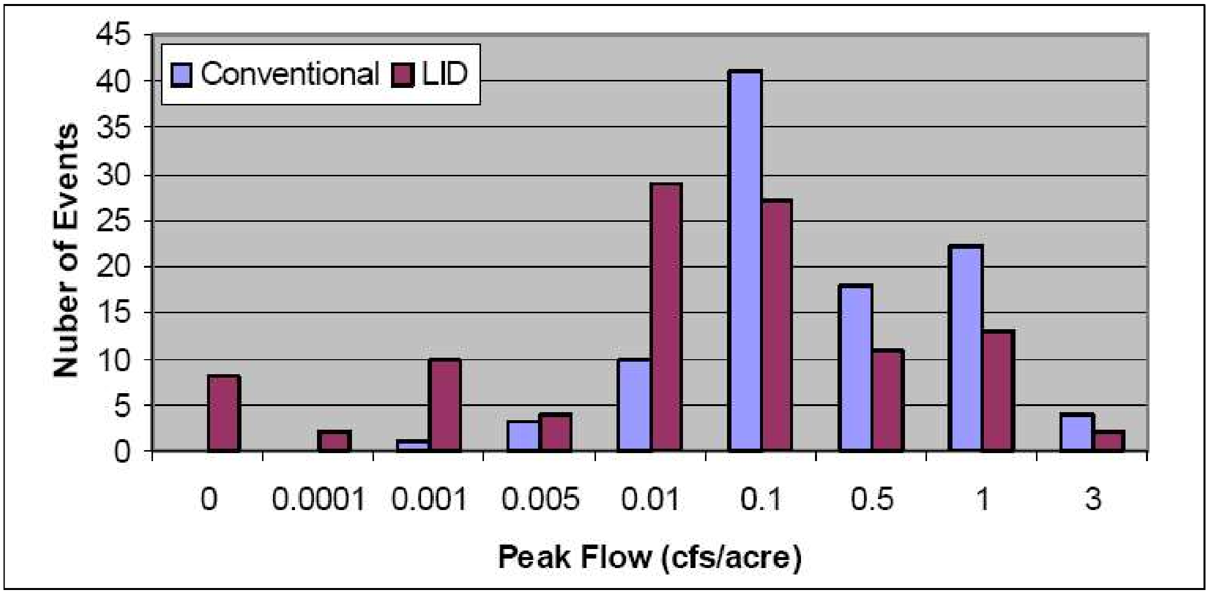


Exhibit 10-10. Frequency of Peak Flow Discharges (Cheng et al. 2003)

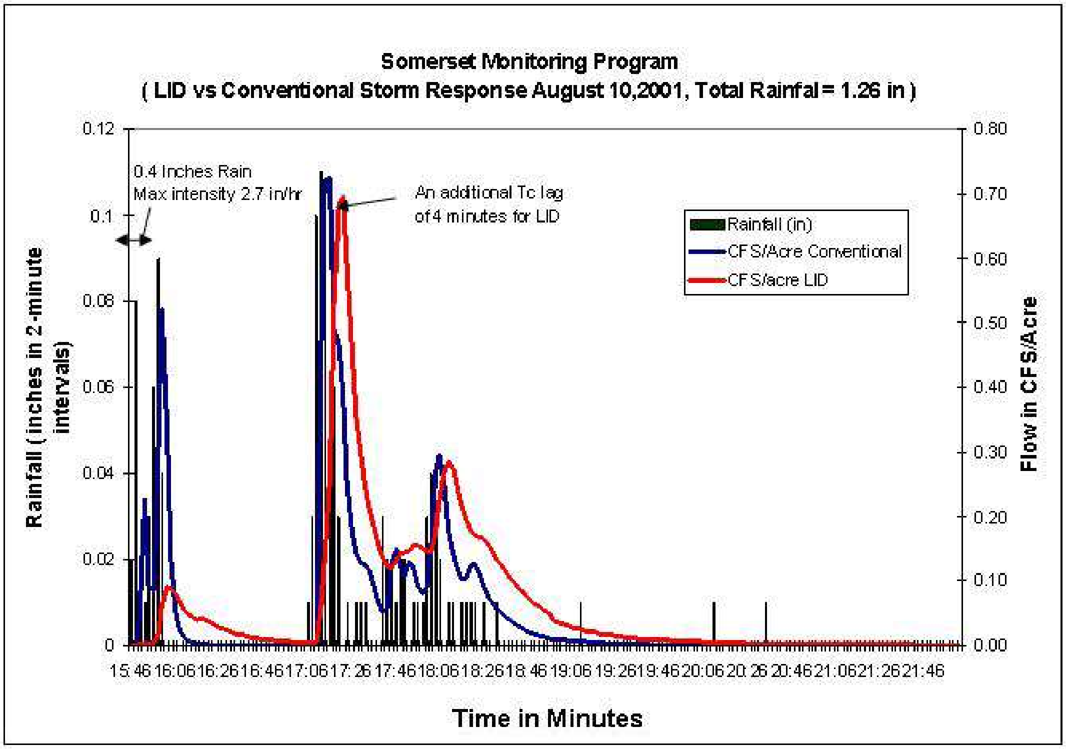


Exhibit 10-11. LID vs. Conventional Storm Responses (Cheng et al. 2003)

10.5 Conclusions

While site level LID studies are still relatively rare compared to practice-level studies, a variety of site level studies do exist and more are expected to be completed in the coming years. To date, most studies have been based on a Reference/Paired Watershed approach, also known as the Before-After/Control Impact (BACI) study method, as is recommended by this Manual. Results of these studies have been interpreted by researchers in ways generally consistent with the recommendations of this Manual. Review of existing studies is a worthwhile undertaking when planning a site level LID monitoring study.

10.6 References

Barr Engineering Company. 2006. *Burnsville Stormwater Retrofit Study*. Prepared for City of Burnsville.

Cheng, M.S., Coffman, L.S., Zhang, Y., and J.Z. Licsko. 2003. *Comparison of Hydrological Responses from Low Impact Development with Conventional Development*. In Proceedings of World Water & Environmental Resources Congress 2003. Environmental and Water Resources Institute (EWRI), American Society of Civil Engineers, Philadelphia, Pennsylvania, June 23-26, 2003.

Clausen, J.C. 2007. *Jordan Cove Watershed Project: Final Report.* Prepared for U.S. Environmental Protection Agency (EPA) and Connecticut Department of Environmental Protection.

Clausen, J.C. and J. Spooner. 1993. *Paired Watershed Study Design*. Prepared for U.S. Environmental Protection Agency (EPA) Office of Water, Washington, D.C. 841-F-93-009.

Selbig, W.R., and R.T. Bannerman. 2008. A *comparison of runoff quantity and quality from two small basins undergoing implementation of conventional- and low-impact-development (LID) strategies*, *Cross Plains, Wisconsin, Water Years 1999–2005*. U.S. Geological Survey (USGS) Scientific Investigations Report 2008–5008. 57 p.

University of Connecticut (UCONN). 2007. Jordan Cove Urban Watershed Project Website. http://jordancove.uconn.edu/ Accessed, October 27, 2009. Use of photos for informational purposes is permitted with attribution.

Appendix A
Stormwater BMP Database Reporting Requirements

Revised: October 26, 2009

Content: This Appendix provides a condensed list of data elements requested for the International Stormwater BMP Database. For descriptions of these data elements, see the User's Guide for the BMP Database. Data entry should be completed in the Excel spreadsheet package downloaded from the project website. Requested fields are identical, but the format is horizontal instead of vertical.

Prioritization of Data: The Database requests a large number of data elements, but not all data elements are required for acceptance of a study. Color coding in the data entry spreadsheet package is provided to help users prioritize the data that they will be able to provide.   Color coding is not provided in this appendix, which is intended to serve as a simple summary of the data elements.

R	Required data
I	Important, but not required for inclusion in the database
N	Nice to Have (supplemental)

Units of Measurement: Units of measurement are required for many fields in the database, but fields for units are not identified in this Appendix for simplicity.

Water Quality Data: the current version of the data entry spreadsheets generally follows EPA's "WQX" format (replacing Legacy STORET). Under this format, particle size distribution data would be entered directly into the water quality data spreadsheet.

Low Impact Development Reporting Protocols: The LID related data elements in this appendix are a first release, developed based on input from an expert advisory panel including Richard Horner, Bill Hunt, Rob Roseen, Rob Traver, Bob Pitt, and Ben Urbonas, as well as the experiences of the Database Project Team.

Appendix A
Stormwater BMP Database Reporting Requirements

GENERAL INFORMATION		
Test Site Name		
City		
County		
State		
Zip Code		
Country		
Site Elevation		
Unit		
Unit System (SI or English)		
Number of Watersheds		
Number of BMPs		
Type of Study Code		
Comments/General Description of Study Site		
Test Site/Study Documentation Information		
Year Submitted to Database		
Data Provider		
Report Title or Data Source		
Report Authors		
Year of Publication		
Report Attached?		
Photos Attached?		
BMP Layout Attached?		
QAPP/ SAP Attached?		
Abstract		
SPONSORING AND MONITORING AGENCIES		
(add other agencies, if needed)	**Agency 1**	**Agency 2**
Agency Name		
Agency Responsibility		
Agency Type Code		
Address 1		
Address 2		
Address 3		
City		
State		
Zip Code		
Country		
Phone		
Fax		
Email		
Location Information		
Climate Station State Code		
Climate Station ID (see picklist)		
Latitude (Decimal)		
Longitude (Decimal)		
Reference Datum		
Hydrologic Unit Code		
EPA Reach Code		
Township		
Range		
Principal Meridian		
Section		
Quarter		
Quarter Quarter		
Quarter Quarter Quarter		
Quad Map Name		
Time Zone		

Appendix A
Stormwater BMP Database Reporting Requirements

Note: the priority level of the requested data varies depending on BMP type. In general, LID-oriented practices must provide a larger amount of watershed data than other practices. See www.bmpdatabase.org for more information.

Watershed	
Watershed Name	
Watershed Type Code	
Watershed Description	
Total Watershed Area	
Total Length of Watershed	
Total Length of Grass-Lined Channels	
Total Disturbed Area	
% Irrigated Lawn and/or Agriculture	
% Total Impervious Area in Watershed	
% of Total Impervious Area that is Hydraulically Connected	
% of Watershed Served by Storm Sewers	
Storm Sewer Design Return Period (yrs)	
Average Watershed Slope	
Average Runoff Coefficient	
Hydrologic Soil Group	
Soil Type	
Type of Vegetation	
Watersheds Roads and Parking Lot Information	
Watershed Name	
Total Paved Roadway Area	
Total Length of Curb and Gutter on Paved Roads	
Total Unpaved Roadway Area	
Total Length of Curb/Gutter on Unpaved Roads	
% Paved Roads Draining to Grass Swales/Ditches	
% Unpaved Roads Draining to Grass Swales/Ditches	
Type of Pavement on Roadways	
Total Paved Parking Lot Area	
Total Length of Curb/Gutter on Paved Parking Lots	
Total Unpaved Parking Lot Area	
Total Length of Curb/Gutter on Unpaved Parking Lots	
% Paved Parking Lot Draining to Grass Swales/Ditches	
% Unpaved Parking Lot Draining to Grass Swales/Ditches	
Type of Pavement in Parking Lots	
% Porous Concrete	
% Porous Asphalt	
% Porous Modular	
Characterize Highway Conditions (see User's Guide)	
Average Annual Daily Traffic (cars/day)	
Number of Lanes	
Deicing Method	
Land Use (provide each type and associated %)	**(from pick list)**

Appendix A
Stormwater BMP Database Reporting Requirements

General BMP Information (Complete for Each BMP at Site)

	Complete for Each BMP at Study Site
Watershed Name	
BMP Name	
Type of BMP Being Tested (*from Pick-List)*	
Basis of Design (e.g., 2-yr, 24 hr storm or design treatment flow rate	
Purpose of BMP (treatment objectives)	
Source of Design Guidance for BMP	
Date Facility Placed in Service	
Number of Inflow Points	
BMP Designed to Bypass or Overflow	
Upstream Treatment Provided?	
Describe Upstream Treatment (if any)	
Name of Upstream BMP(s) (comma separated list upstream to downstream)	
General Configuration of BMP in Tributary Watershed (i.e, end of pipe, source control, off-line, on-line)	
Was qualified engineering oversight provided at construction? (Y/N)	
Was structure installed as designed? (Y/N)	
General Description of Site Activities/Conditions Influencing Pollutant Loading to BMP	
Maintenance and Conditions of BMP	
Maintenance Type and Frequency	
Last Rehabilitation Date	
Type of Rehabilitation	
Description, Types, and Designs of Outlets	
Qualitative Evaluation of BMP Condition (vegetation, soils, odors, etc.)	
For BMPs without permanent pool, does surface ponding exist beyond design drain time?	
If clogging present, estimate % of total surface area of structure affected	
Describe BMP/Comments	

BMP Cost Data (if available)

Cost Basis	Year of Cost Estimate	
Total Facility Costs (Base Cost of Original Design, Construction and Installation of BMP,	Total Facility Costs	
	Description of Items Included in Total Facility Cost	
Routine Maintenance Costs	Average Annual Routine Maintenance Costs ($/year)	
Periodic Rehabilitation Costs	Average Corrective and Infrequent Maintenance Costs ($/event)	
Supplemental Facility Cost Information:	Excavation/ Clearing Costs	
	Structural Materials Costs	
	Facility Installation/ Construction Costs	
	Structural Control Devices Costs	
	Vegetation and Landscaping Costs	
	Engineering and Overhead Costs	
	Land Costs or Value	

Appendix A
Stormwater BMP Database Reporting Requirements

Detention (Dry) Basin Design Information	
BMP Name	
Water Quality Detention Volume	
Water Quality Detention Surface Area When Full	
Water Quality Detention Basin Length	
Detention Basin Bottom Area	
Brim-full Volume Emptying Time (hrs)	
Half Brim-full Volume Emptying Time (hrs)	
Bottom Stage Volume, If Any	
Bottom Stage Surface Area, If Any	
Is there a micro pool? (Yes/No)	
Forebay Volume	
Forebay Surface Area	
Vegetation Cover Within Basin	
Flood Control Volume, If Any	
Design Flood Return Periods (yrs)	
Depth to Water Table	
Retention (Wet) Pond Design Information	
BMP Name	
Volume of Permanent Pool	
Permanent Pool Surface Area	
Permanent Pool Length	
Littoral Zone Surface Area	
Littoral Zone Plant Species	
Water Quality Surcharge Detention Volume When Full	
Water Quality Surcharge Surface Area When Full	
Water Quality Surcharge Basin Length	
Brim-full Emptying Time (hrs) for Surcharge	
Half Brim-full Emptying Time (hrs) for Surcharge	
Forebay Volume	
Forebay Surface Area	
Vegetation Cover Within Basin Above Permanent Pool	
Flood Control Volume	
Design Flood Return Periods (yrs)	
Grass Filter Design Information	
BMP Name	
Grass Strip's Length	
Grass Strip's Width	
Longitudinal Slope	
Flow Depth during 2-Year Storm	
2-Year Peak Flow Velocity	
Grass Species and Densities	
Is Strip Irrigated?	
Manning's n During 2-year Flow	
Depth to Groundwater or Impermeable Layer	
Saturated Infiltration Rate	
Hydrologic Soil Group	

Appendix A
Stormwater BMP Database Reporting Requirements

Media Filter Design Information	
BMP Name	
Permanent Pool Volume Upstream of Filter Media, If Any	
Permanent Pool's Surface Area Preceding Filter	
Permanent Pool's Length Preceding Filter	
Surcharge Detention Volume, Including Volume Above Filter Bed	
Surcharge Detention Volume's Surface Area, Including Area Above Filter Bed	
Surcharge Detention Volume's Length	
Surcharge Detention Volume's Design Depth	
Surcharge Detention Volume's Drain Time in Hours	
Media Filter's Surface Area	
Angle of Sloping or Vertical Filter Media in Degrees (0 to 90)	
Number of Media Layers in Filter	
Type and Depth (or Thickness) of Each Filter Media Layer	
Porous Pavement Design Information	
BMP Name	
Pavement Type (from drop-down list)	
Ratio of Tributary Area to Pavement Surface Area (hydraulic loading)	
Purpose of Porous Pavement	
Description and Dimensions of Surface Layer	
Type of Binder (e.g., PG64-28)	
Admixtures Used in Mix (i.e., poly fibers, SBS, SBR, etc)	
Surface Infiltration Rate (at time of study)	
Design Infiltration Rate (including safety factor for clogging)	
Porous Pavement Surface Area	
Slope	
Is grass growing in modular pores?	
If yes, is grass healthy?	
Total Storage Volume Above Pavement, If Any	
Estimated Drain Time (hrs) of Storage Volume Above Pavement, If Any	
Description and Dimensions of Aggregate Base	
Type of Granular or Soil Materials Used in or Below Pavement	
% Porosity of Granular or Soil Materials (void space)	
Total Storage Volume in the Granular Media Below Pavement	
Estimated Drain Time (hrs) of Porous Media Volume	
Description and Dimensions of Separation Layer	
Description and Dimensions of Water Quality Treatment Layer, if present	
Degree of Compaction of Pavement Subbase	
Does Porous Pavement Have Underdrains?	
Underdrain Description	
Depth of Underdrain Below Surface, if present	
Depth to Groundwater	
Depth to Impermeable Layer	
NRCS Hydrologic Soil Group	
Infiltration Rate	
Groundwater Hydraulic Conductivity	
Groundwater Flow Gradient	
Depth of Each Soil Layer Below Pavement	

Appendix A
Stormwater BMP Database Reporting Requirements

Infiltration Basin Design Information	
BMP Name	
Capture Volume of Basin	
Surface Area of Capture Volume When Full	
Infiltrating Surface Area	
Basin Length	
Depth to Groundwater	
Depth to Impermeable Layer	
Hydrologic Soil Group	
Depth and Type of Each Soil Layer Below Basin	
Infiltration Rate	
Plant Species on Infiltrating Surface	
Granular Material on Infiltrating Surface	
Hydraulic Conductivity of Underlying Soils	
Groundwater Flow Gradient	
Flood Control Volume above Water Quality Detention Volume	
Design Flood Control Return Periods	
Purpose of Basin	
Percolation Trench and Dry Well Design Information	
BMP Name	
Percolation Trench/ Well Surface Area	
Percolation Trench/Well Length	
Percolation Trench/Well Depth	
Depth to Groundwater	
Depth to Impermeable Layer	
Depth and Type of Each Soil Layer	
Type and Gradation of Granular Materials Used	
Was geotextile fabric used above granular trench fill?	
Was geotextile used on the sides of granular fill?	
Was Geotextile Used On the Bottom of Granular Fill?	
Porosity of Granular Material	
Total Storage Volume	
Type of Geotextile Used	
Hydraulic Conductivity of Soils	
Groundwater Flow Gradient	
Purpose of Trench or Well	
Wetland Channel and Swale Design Information	
BMP Name	
Length of Channel/Swale	
Longitudinal Slope of Channel/Swale	
Bottom Width of Channel/Swale	
Side Slope of Channel/Swale	
Average Longitudinal Inflow Spacing	
2-Year Flow Design Depth in Channel/Swale	
2-Year Peak Design Flow Velocity	
2-Year Manning's n	
Depth to High Groundwater	
Groundwater Hydraulic Conductivity	
Plant Species in Wetland Zone/Swale	
Maximum Design Flow Capacity Return Periods	

Appendix A
Stormwater BMP Database Reporting Requirements

Wetland Basin Design Information	
BMP Name	
Volume of Permanent Pool	
Permanent Pool Surface Area	
Permanent Pool Length	
Water Quality Surcharge Detention Volume When Full	
Water Quality Surcharge Surface Area, When Full	
Water Quality Surcharge Basin Length, When Full	
Brim-full Emptying Time (hrs)	
Half Brim-full Emptying Time (hrs)	
Forebay Volume	
Forebay Surface Area	
Flood Control Volume	
Design Flood Return Periods (yrs)	
Wetland Surface Area	
% of Pond with 6" (0.15 m) Depth	
% of Pond with 12" (0.3 m) Depth	
% of Pond with 12" - 24" (0.3-0.6 m) Depth	
% of Pond with 24" to 48" (0.6-1.3 m) Depth	
% of Pond with >48" (1.3 m) Depth	
% of Wetland Basin Area Without Standing Water (Meadow)	
Plant Species in the Wetland	
Manufactured Device Design Information	
BMP Name	
Device Type (from pick list)	
Device Name, Model and Purchase Date (according to Manufacturer)	
Primary Unit Treatment Process (from pick-list)	
Secondary Unit Treatment Process (from pick list)	
Tertiary Unit Treatment Process (from pick list)	
Narrative Description of Additional Treatment Processes	
Description of Sizing Methodology	
Targeted Pollutants (for solids, indicate targeted particle size)	
Describe Design Inflow Rate(s) for Treatment (include maximum rate, if different)	
Describe Design Loading Capacity (Flow/Unit Surface Area)	
Describe Design Outflow Rate	
Manufacturer-recommended Maintenance Requirements/Frequency	
Primary Flow Control (if applicable)	
Outfall Type (gravity or pumped)	
Outlet Description	
Design Water Quality Surcharge/Detention Volume	
Surcharge Surface Area	
Surcharge Length	
Surcharge Depth	
Brim-full Emptying Time (hrs) for Surcharge	
If Wet Vault: Volume of Permanent Pool	
If Wet Vault: Permanent Pool Surface Area	
If Wet Vault: Permanent Pool Depth	
If Wet Vault: Permanent Pool Length	
If Media Filter or Insert: Filter or Insert Surface Area	
If Media Filter or Insert: Filter or Insert Thickness	
If Media Filter or Insert: Describe Filter or Insert Media Type/Material	
If Multi-chambered: Overflow Baffle/Weir Description	
If Multichambered: Underflow Baffle/Weir Description	
Comments	

Device Type Pick-list	Unit Treatment Process Pick List
Oil & Water Separator	Hydrologic: Volume Reduction
Flow through – single-chamber	Hydrologic: Peak Flow Attenuation
Flow through – multi-chamber	Physical: Density/Gravity/Inertial Separation Including Sedimentation
Volume capture – extended detention w/ pool	Physical: Screening/Filtration
Volume capture – extended detention w/o pool	Physical: UV Disinfection
Media filter – single-chamber	Physical: Sorption
Media filter – multi-chamber	Biological: Microbially Mediated Transformation
Inlet insert	Biological: Vegetative Uptake and Storage
Multi-chambered treatment train	Chemical: Ion Exchange
Underground infiltration chamber	Chemical: Coagulant/Flocculent Injection
High-rate biofiltration unit	Chemical: Sorption
Other	Chemical: Disinfection
	Other (describe in comments)

Appendix A
Stormwater BMP Database Reporting Requirements

Bioretention Design Information	
BMP Name	
Type of Bioretention (pick from drop-down list)	
Ratio of Tributary Area to Bioretention Surface Area (hydraulic loading)	
Is Pretreatment Provided? (Y/N)	
Description of Pretreatment, if present	
Description of Flow Entrance	
Bioretention Surface Area	
Ponding Volume above Bioretention Media Surface	
Average Ponding Depth above Bioretention Media Surface	
General Shape of Bioretention Feature (triangle, oval, rectangle, etc.)	
Is "Internal Water Storage Zone" Created? (Y/N) (via underdrain placement above bottom of media layer)	
Subsurface Storage Volume	
If subsurface storage provided, then height of outlet above bottom of bioretention media	
Bioretention Media: Natural or Amended	
Bioretention Media Depth	
Bioretention Media Design Specifications	
Bioretention Media "P" Index (Phosphorus)	
Description of Supplemental Bioretention Media Characteristics: (clay content, pH, cation exchange capacity, carbon:nitrogen ratio, moisture content, metals contents, inerts content)	
Description of Vegetation Community (canopy layers and their approximate cover [stems/acre], species)	
Description of Mulch (if present)	
Surface Infiltration Rate	
Design Infiltration Rate (including safety factor for clogging)	
Is an Underdrain Provided? (Y/N)	
Description and Dimensions of Underdrain, if present	
Underdrain Gravel Layer Thickness, if present	
Description and Dimensions of Surface Overflow, if present	
Is a Hydraulic Restriction Layer (Liner) Provided? (Y/N)	
Description of Hydraulic Restriction Layer, if present	
Seasonal High Water Table Position Relative to Invert	
Comments	
Green Roof Design Information	
BMP Name	
Roof Type (Intensive or Extensive)	
Purpose of Roof	
Describe Green Roof	
Describe Vegetation	
Supplemental Irrigation Provided?	
Roof Media's Surface Area	
Roof Slope	
Angle of sloping or vertical filter media in degrees (0 to 90)	
Number of Media Layers	
Type and Depth (or Thickness) of Each Media Layer	
% Compost or Organic Material of Media at Installation	
Roofing Material	
Detention Volume	
Detention Volume's Drain Time in Hours	

Drop-down list of Bioretention Types
Bioretention cell—Non-linear, not associated with conveyance
Off-line bioretention area—Placed next to swale at lower elevation to increase storage
In-line bioretention area—Linear, incorporating cell and swale characteristics for conveyance as well as retention and treatment, but low velocity
Sloped (weep garden) bioretention area—Behind retaining wall on relatively steep gradient
Sloped biodetention vegetative barrier—Placed along slope contour to retard runoff
Tree box filter—Enlarged planting pit, usually with drain inlet and underdrain

Appendix A
Stormwater BMP Database Reporting Requirements

Stormwater Harvesting (Cisterns/Rain Barrels)	
BMP Name	
Basic System Description (e.g., tank, cistern, or rain barrel; water source, water use, distribution system)	
Number of Units in Watershed	
Contributing Rooftop Size	
Roofing and Gutter Material Description	
Storage Volume	
Drain Time at Capacity (minutes)	
Expected Long-term Capture Volume (based on computer simulation)	
Model Used for Capture Volume Simulation	
% Bypass Associated with System	
Describe Emergency Spillage (Overflow) Provision	
Describe Mosquito Prevention (if any)	
Intended Use of Captured Water (e.g., irrigation, toilet flushing, etc.)	
Can Potable Water Supplement Tank? (Y or N)	
Type of Irrigation System (e.g., spray, drip, hand) (if applicable)	
Reason System Selected (stormwater capture, supplement water supply, etc.)	
Comments	
Nonstructural General Information	
BMP Name	
Type of Nonstructural BMP Being Tested	
Date Test Began	
Description of Quantity or Measure of BMP	
Other BMP Type	
BMP Name	
Describe Key Structural Features	
Describe Key Landscaping/Vegetation Features	

Appendix A
Stormwater BMP Database Reporting Requirements

Low Impact Development at Site Level Design Information (Primary Source: Richard Horner, 2009)		
Data Element	**Brief Description**	
BMP Name (Overall LID Site Name)	User-defined site name relates back to "General BMP" data entry spreadsheet.	
Describe Site Design (include key elements of design)	Provide "big picture" of site design objectives and key design elements.	
Describe Monitoring Design (to ensure proper use of data)	Describe monitoring design relationship to design elements.	
Method for Flood Control	Used to assess extent to which LID is used for water quality and flood control, or water quality only. Some LID sites have "hybrid" characteristics incorporating LID practices with traditional flood control approaches (e.g., are centralized detention and LID techniques).	
Instructions: Quantitative data should be provided to the extent it is available. If the practice is not implemented, this should be stated instead of leaving the field blank. For discrete practices (e.g., permeable pavement, bioretention, design data should also be provided in their respective BMP tables).		
Conservation Features	Conserving natural areas includes preservation of existing trees, other vegetation, and soils.	
Minimizing Disturbance	Minimizing disturbance included minimizing soil excavation and compaction and vegetation disturbance.	
Minimizing Building Coverage	Minimizing building coverage includes minimizing impervious rooftops and building footprints.	
Minimizing Travelway Coverage	Minimizing travelway coverage includes constructing streets, driveways, sidewalks, and parking lot aisles to the minimum widths necessary, provided that public safety and a walkable environment for pedestrians are not compromised.	
Maintaining Natural Drainage Patterns and Designing Drainage Paths to Increase Time of Concentration	Maintaining natural drainage patterns and designing drainage paths to increase time of concentration includes measures such as: maintaining depressions and natural swales; emphasizing sheet flow instead of concentrated flow; increasing the number and lengths of flow paths; maximizing non-hardened drainage conveyances; and maximizing vegetation in areas that generate and convey runoff.	
Source Controls	Source controls include minimizing pollutants; isolating pollutants from contact with rainfall or runoff by segregating, covering, containing, and/or enclosing pollutant-generating materials, wastes, and activities; conserving water to reduce non-stormwater discharges.	
Permeable Pavements*	Permeable pavements include constructing low-traffic areas with permeable surfaces such as porous asphalt, open-graded Portland cement concrete, coarse granular materials, concrete or plastic unit pavers, and plastic grid systems. Representative applications may include driveways, patio slabs, walkways and sidewalks, trails, alleys, and overflow or otherwise lightly-used parking lots.	
Natural Drainage System Elements	Natural drainage system elements include bioretention areas (rain gardens), vegetated swales, vegetated filter strips and other similar features.	
Stormwater Harvesting*	Rainwater harvesting includes use of cisterns, rain barrels or rain storage units.	
Green Roof (vegetated)*	Green roofs include vegetated roofs with stormwater-related design components.	
Other Site Features (including traditional BMPs)	Enables user to define other key site features or traditional BMPs.	
List BMPs Monitored Within LID Site (as entered into BMP Database)	Relates overall LID site design to individual practices monitored and/or implemented at the site (e.g., bioretention, permeable pavement).	
Estimate of Hydrologically Available Temporary Storage at Site	See Monitoring Guidance Manual for a detailed discussion. This information helps to normalize the relationship between source areas and storage areas, both in terms of routing and relative volume for purposes of comparing LID sites. Tabular estimates of detained, retained and excess volume for a range of storm events are beneficial in developing these estimates. A PDF providing this information can be attached separately, or this information can be summarized narratively. Also provide units of measurement (e.g., acre-feet, watershed inches).	
Estimated Storage Recovery Rate in Watershed (days)	Describes the time for the LID site to recover hydrologically available temporary storage. Estimates of minimum, maximum and average recovery rates for retained and detained volumes should be provided. See Monitoring Guidance Manual for additional information.	
Describe Key Weather Parameters During Study Period (e.g., ET, temperature,etc.)	Weather conditions can significantly affect the water balance of LID sites. Frozen soils can reduce infiltration rates; conversely, high ET can increase evapotranspiration rates. Characterization of ET, temperature and other similar factors are important in normalizing comparisons among LID sites.	
Comments/Other Description	Allows user to describe other unique aspects of the site design or other general comments.	

Appendix A
Stormwater BMP Database Reporting Requirements

Monitoring Related Data Are Summarized Below (with priority identified) and Should be Accessed in Tabular Form from the Data Entry Spreadsheet Package Available for Download at www.bmpdatabase.org

Monitoring Stations

Monitoring Station Information (for each monitoring station)	**Priority**
Station Name	R
Comments	R
Monitoring Station Relationship to BMP	
BMP Name	R
Station Name	R
Relationship to BMP (inflow, outflow, etc.)	R
Instrument Types at Each Monitoring Station (from drop-down pick lists)	
Station Name	R
Date Instrument Installed	I
Instrument Type Code (e.g., gage, meter)	I
Data Type Code (e.g., water quality, flow)	I
Type of Control Structure	I
Comments	

Monitoring Costs	
Fixed Stations:	
Monitoring Year	N
Comments	N
Year of Cost Basis	N
Equipment Costs	N
Maintenance Costs	N
Sampling Costs	N
Laboratory Costs	N
Temporary Stations:	N
Year of Cost Basis	N
Equipment Costs	N
Sampling Costs	N
Laboratory Costs	N

Monitoring Data

Monitoring Event Description (general information for each event)	**Priority**
Event Number	R
Event Start Date	R
Event Start Time	R
Event Type	R
Antecedent Dry Period (hrs)	I
Description of Antecedent Watershed/Facility Conditions (e.g., key field notes, frozen ground, facility storage available, etc.)	I
QA/QC Description	I
Comments	N
Precipitation Data	
Enter Previously Defined Event #	R
Monitoring Station Name	R
Start Date	I
Start Time	I
End Date	I
End Time	I
Total Depth	R
Peak One Hour Precip. Rate	I
Flow Data	
Previously Defined Event #	R
Monitoring Station Name	R
Flow Start Date	R
Flow Start Time	I
Flow End Date	I
Flow End Time	I
Total Flow Volume	R
Peak Flow Rate	I
Total Bypass Volume	R
Peak Bypass Flow Rate	I
Baseflow Rate	I
% Hydrograph Captured	N
Estimate of De Minimus Flow Contributions (not measured)	N

Water Quality Data	**Priority**
Event # (previously defined)	R
Monitoring Station (previously defined)	R
Water Quality Sampling Start Date	R
Water Quality Sampling Start Time	I
Sample Medium (e.g., water, soil)	R
Sample Type	R
# of Samples, if Composite	I
WQX Characteristic (Water Quality Constituent from Pick List)	R
Sample Fraction (e.g., dissolved, total)	R
Result Value	R
Units	R
Qualifier	R
Detection Limit	I
Detection Limit Type	I
Analysis Method	I
Appropriate for Performance Analysis? (Yes or No)	I
Result Comment	N
Settling Velocity Distribution Data	
Previously Defined Event #	N
Monitoring Station	N
10%	N
20%	N
30%	N
40%	N
50%	N
60%	N
70%	N
80%	N
90%	N
100%	N

Priority Codes

R	Required data
I	Important, but not required for inclusion in the database
N	Nice to Have (supplemental)

APPENDIX B ASSESSMENT OF APPROACHES TO EVALUATING BMP PERFORMANCE

Overview of Approaches to Evaluate BMP Performance

A variety of pollutant removal methods have been utilized in BMP monitoring studies to evaluate efficiency. This section describes and gives examples of methods employed by different investigators. Historically, one of six methods has been used by investigators to calculate BMP efficiency:

- Efficiency ratio
- Summation of loads
- Regression of loads
- Mean concentration
- Efficiency of individual storm loads
- Reference watersheds and before/after studies

Although use of each of these methods provides a single number that summarizes efficiency of the BMP in removing a particular pollutant, they are not designed to look at removal statistically, and thus, do not provide enough information to determine if the differences in inflow and outflow water quality measures are statistically significant.

Efficiency Ratio

Definition

The efficiency ratio is defined in terms of the average event mean concentration (EMC) of pollutants over some time period:

$$ER = 1 - \frac{\text{average outlet EMC}}{\text{average inlet EMC}} = \frac{\text{average inlet EMC - average outlet EMC}}{\text{average inlet EMC}}$$

EMCs can be either collected as flow weighted composite samples in the field or calculated from discrete measurements. The EMC for an individual event or set of field measurements, where discrete samples have been collected, is defined as:

$$EMC = \frac{\sum_{i=1}^{n} V_i C_i}{\sum_{i=1}^{n} V_i}$$

where,

V: volume of flow during period i
C: average concentration associated with period i
n: total number of measurements taken during event

The arithmetic average EMC is defined as:

$$\text{average EMC} = \frac{\sum_{j=1}^{m} EMC_j}{m}$$

where,

m: number of events measured

In addition, the log mean EMC can be calculated using the logarithmic transformation of each EMC. This transformation allows for normalization of the data for statistical purposes.

$$\text{Mean of the Log EMCs} = \frac{\sum_{j=1}^{m} Log\left(EMC_j\right)}{m}$$

Estimates of the arithmetic summary statistics of the population (mean, median, standard deviation, and coefficient of variation) should be based on their theoretical relationships (Appendix A) with the mean and standard deviation of the transformed data. Computing the mean and standard deviation of log transforms of the sample EMC data and then converting them to an arithmetic estimate often obtains a better estimate of the mean of the population due to the more typical distributional characteristics of water quality data. This value will not match that produced by the simple arithmetic average of the data. Both provide an estimate of the population mean, but the approach utilizing the log-transformed data tends to provide a better estimator, as it has been shown in various investigations that pollutant, contaminant, and constituent concentration levels tend to be well described by a log-normal distribution (EPA 1983). As the sample size increases, the two values converge.

Assumptions

This method:

- Weights EMCs from all storms equally regardless of relative magnitude of storm. For example, a high concentration/high volume event has equal weight in the average EMC as a low concentration/low volume event. The logarithmic data transformation approach tends to minimize the difference between the EMC and mass balance calculations.

- Is most useful when loads are directly proportional to storm volume. For work conducted on nonpoint pollution (i.e., inflows), the EMC has been shown to not vary significantly with storm volume. Accuracy of this method will vary based on the BMP type.

- Minimizes the potential impacts of smaller/”cleaner” storm events on actual performance calculations. For example, in a storm by storm efficiency approach, a low removal value for such an event is weighted equally to a larger value.

- Allows for the use of data where portions of the inflow or outflow data are missing, based on the assumption that the inclusion of the missing data points would not significantly impact the calculated average EMC.

Comments

- This method is taken directly from non-point pollution studies and does a good job characterizing inflows to BMPs but fails to take into account some of the complexities of BMP design. For example, some BMPs may not have outflow EMCs that are normally distributed (e.g., media filters and other BMPs that treat to a relatively constant level that is independent of inflow concentrations).

- This method also assumes that if all storms at the site had been monitored, the average inlet and outlet EMCs would be similar to those that were monitored.

- Under all circumstances this method should be supplemented with an appropriate non-parametric (or if applicable parametric) statistical test indicating if the differences in mean EMCs are statistically significant (it is better to show the actual level of significance found, than just noting if the result was significant, assuming a 0.05 level).

Example

The example calculations given below are for the Tampa Office Pond using arithmetic average EMCs in the efficiency ratio method.

Table B.1: Example of ER Method results for TSS in the Tampa Office Pond

Period of Record	Average EMC In	Average EMC Out	Efficiency Ratio
1990	27.60	11.18	59%
1993-1994	34.48	12.24	64%
1994-1995	131.43	6.79	95%
ER is rounded, but the other numbers were not (to prevent introduction of any rounding errors in the calculations)			

Summation of Loads

Definition

The summation of loads method defines the efficiency based on the ratio of the summation of all incoming loads to the summation of all outlet loads, or:

$$\text{SOL} = 1 - \frac{\text{sum of outlet loads}}{\text{sum of inlet loads}}$$

The sum of outlet loads are calculated as follows:

$$\text{sum of loads} = \sum_{j=1}^{m}\left(\sum_{i=1}^{n} C_i V_i\right) = \sum_{j=1}^{m} EMC_j \cdot V_j$$

Assumptions

- Removal of material is most relevant over entire period of analysis.
- Monitoring data accurately represents the actual entire total loads in and out of the BMP for a period long enough to overshadow any temporary storage or export of pollutants.
- Any significant storms that were not monitored had a ratio of inlet to outlet loads similar to the storms that were monitored.
- No materials were exported during dry periods, or if they were, the ratio of inlet to outlet loads during these periods was similar to the ratio of the loads during the monitored storms.

Comments

- A small number of large storms typically dominate efficiency.

- If toxics are a concern then this method does not account for day-to-day releases, unless dry weather loads in and out are also accounted for. In many cases long-term dry weather loads can exceed those resulting from wet weather flows.

- Under all circumstances this method should be supplemented with an appropriate non-parametric (or if applicable parametric) statistical test indicating if the differences in loads are statistically significant (it would be better to show the actual level of significance found, rather than just noting if the result was significant, assuming a 0.05 level).

Example

The example calculations given in Table B.2 are for the Tampa Office Pond using a mass balance based on the summation of loads.

Table B.2: Example of SOL Method results for TSS in the Tampa Office Pond

Period of Record	Sum of Loads In (kg)	Sum of Loads Out (kg)	SOL Efficiency
1990	134.60	39.67	71%
1993-1994	404.19	138.44	66%
1994-1995	2060.51	130.20	94%
SOL Efficiency is rounded, but the other numbers were not (to prevent introduction of any rounding errors in the calculations)			

Regression of Loads (ROL)

Definition

The regression of loads method as described by Martin and Smoot (1986) defines the regression efficiency as the slope (β) of a least squares linear regression of inlet loads and outlet loads of pollutants, with the intercept constrained to zero. The zero intercept is specified as an "engineering approximation that allows calculation of an overall efficiency and meets the general physical condition of zero loads-in (zero rainfall) yield zero loads-out". The equation for the ROL efficiency is:

$$\text{Loads out} = \beta \bullet \text{Loads in} = \beta - \frac{\text{Loads out}}{\text{Loads in}}$$

The percent reduction in loads across the BMP is estimated as:

$$\text{Percent Removal} = 1 - \beta = 1 - \frac{\text{Loads out}}{\text{Loads in}}$$

Due to the nature of stormwater event monitoring, it is rare that all of the assumptions for this method are valid, particularly requirements for regression analysis. The example calculations and plots provided in this section are from one of the better studies available at the time this manual was written, and as can be seen from the ROL plots, the data does not meet the requirements for proper simple linear regression analysis.

Assumptions

- Any significant storms that were not monitored had a ratio of inlet to outlet loads similar to the storms that were monitored. The slope of the regression line would not significantly change with additional data.

- No materials were exported during dry periods, or if they were, the ratio of inlet to outlet loads during these periods was similar to the ratio of the loads during the monitored storms.

- The data is well represented by a least squares linear regression, that is:

    - The data is "evenly" spaced along the x-axis.

    - Using an analysis of variance on the regression, the slope coefficient is significantly different from zero (the p value for the coefficient should typically be less than 0.05, for example).

    - A check of the residuals shows that the data meets regression requirements. The residuals should be random (a straight line on probability paper) and the residuals should not form any trend with predicted value or with time (i.e., they form a band of random scatter when plotted).

Comments

- A few data points often control the slope of the line due to clustering of loads about the mean storm size. Regressions are best used where data is equally populous through the range to be examined. This is readily observed in the examples that follow (See Figures B.1 through B.3).

- The process of constraining the intercept of the regression line to the origin is questionable and in some cases could significantly misrepresent the data. It may be more useful to apply the *Regression of Loads* method over some subset of the data without requiring that the intercept be constrained to the origin. The problem with this alternative approach is that a large number of data points are required in order to get a good fit of the data. Often a meaningful regression cannot be made using the data that was collected. This is well illustrated by the very low R^2 values in the table below. Forcing the line through the origin, in these cases, provides a regression line even where no useful trend is present.

- There is sufficient evidence that this first order polynomial (straight line) fit is not appropriate over a large range of loadings. Very small events are much more likely to demonstrate low efficiency where larger events may demonstrate better overall efficiency depending on the design of the BMP.

Table B.3: Example of ROL Method results for TSS in the Tampa Office Pond

Period of Record	Slope of Regression Line	R^2	Percent Removal
1990	0.21	0.06	79%
1993-1994	0.18	-0.06	82%
1994-1995	0.05	0.46	95%
Percent Removal is rounded, but the other numbers were not (to prevent introduction of any rounding errors in the calculations)			

The regressions used to arrive at the above slopes are given in Figures B.1-B.3.

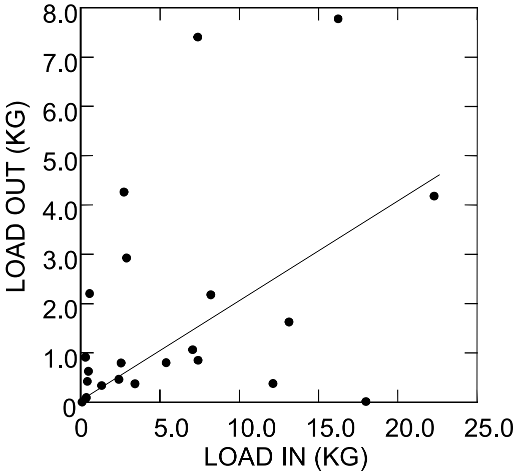


Figure B.1: ROL Plot for use in Calculating Efficiency for TSS using the Tampa Office Pond (1990) (Slope = 0.2135, R^2 = 0.0563, Standard Error in Estimate = 2.176, one point is considered an outlier with a Studentized Residual of 3.304). All points were used for regression. Method is not valid due to failure of simple linear regression assumptions.

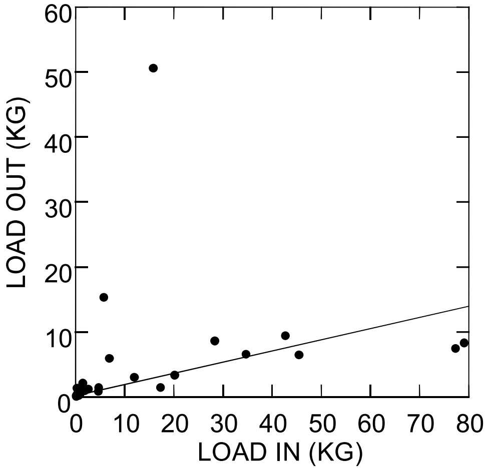


Figure B.2: ROL Plot for use in Calculating Efficiency for TSS using the Tampa Office Pond (1993-1994) (Slope = 0.1801, R^2 = -0.0562, Standard Error in Estimate = 10.440, one point is considered an outlier with a Studentized Residual of 13.206 and one point has a high Leverage of 0.323). All points were used for regression. Method is not valid due to failure of simple linear regression assumptions.

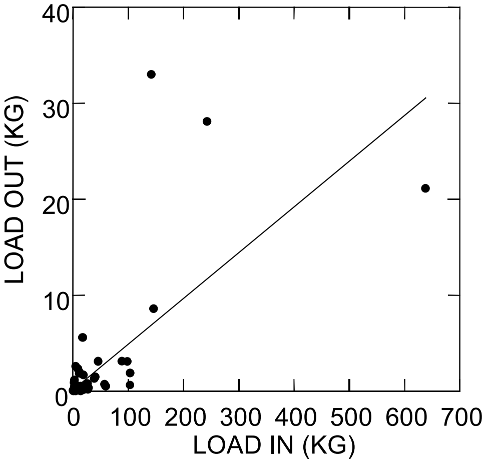


Figure B.3: ROL Plot for use in Calculating Efficiency for TSS using the Tampa Office Pond (1994-1995) (Slope = 0.0492, R^2 = 0.4581, Standard Error in Estimate = 5.260, three points are considered outliers (Studentized Residuals of 3.724, 8.074, and –4.505, the point to the far right on the graph has large Leverage (0.724) and Influence, Cook Distance = 36.144). All points were used for regression. Method is not valid due to failure of simple linear regression assumptions.

Mean Concentration

Definition

The mean concentration method defines the efficiency as unity minus the ratio of the average outlet to average inlet concentrations. The equation using this method is:

$$\text{Mean Concentration} = 1 - \frac{\text{average outlet concentration}}{\text{average inlet concentration}}$$

This method does not require that concentrations be flow weighted. This method might have some value for evaluating grab samples where no flow weighted data is available or where the period of record does not include the storm volume.

Assumptions

- The flows from which the samples were taken are indicative of the overall event.

Comments

- This method might be useful for calculating BMP's effectiveness in reducing acute toxicity immediately downstream of the BMP. This is due to the fact that acute toxicity is measured as a threshold concentration value of a specific constituent in the effluent at or near the point of discharge.

- This methods weights individual samples equally. Biases could occur due to variations in sampling protocols or sporadic sampling (i.e., collecting many samples close in time and others less frequently). The sample collection program specifics are not accounted for in the method and estimated efficiencies are often not comparable between studies.

- There is appreciable lag time for most BMPs between when a slug of water enters a BMP and when the slug leaves the BMP. Unless this lag time is estimated (e.g., through tracer studies) results from this approach can be quite inaccurate. Results of this method may be particularly difficult to interpret where lag time is ignored or not aggressively documented.

- This method does not account for storage capacity. Typically BMPs will have an equal or lesser volume of outflow than of inflow. On a mass basis this affects removal, since volume (or flow) is used with concentration to determine mass for a storm event:

$$1 - \frac{C_{\text{out}} V_{out}}{C_{in} V_{in}} \geq 1 - \frac{\text{average outlet concentration}}{\text{average inlet concentration}}$$

where,

C_{in}: Concentration In
C_{out}: Concentration Out
V_{in}: Volume In
V_{out}: Volume Out

In this respect, it is often more conservative (i.e., lower removal efficiency stated) to use a concentration rather than mass-based removal approach.

Efficiency of Individual Storm Loads

Definition

The Efficiency of Individual Storm Loads (ISL) method calculates a BMP's efficiency for each storm event based on the loads in and the loads out. The mean value of these individual efficiencies can be taken as the overall efficiency of the BMP. The efficiency of the BMP for a single storm is given by:

$$\text{Storm Efficiency} = 1 - \frac{Load_{out}}{Load_{in}}$$

The average efficiency for all monitored storms is:

$$\text{Average Efficiency} = \frac{\sum_{\text{j}=1}^{m} \text{Storm Efficiency}_{\text{j}}}{m}$$

where,

m: number of storms

Assumptions

- Storm size or other storm factors do not play central roles in the computation of average efficiency of a BMP.
- Storage and later release of constituents from one storm to the next is negligible.
- The selection of storms monitored does not significantly skew the performance calculation.

Comments

- The weight of all storms is equal. Large storms do not dominate the efficiency in this scenario. The efficiency is viewed as an average performance regardless of storm size.
- Some data points cannot be used due to the fact that there is not a corresponding measurement at either the inflow or the outflow for a particular storm, and thus efficiency cannot always be calculated on a storm-by-storm basis. This is not true for the ER method, however it is a limitation of the Summation of Load Method.
- Storm by storm analysis neglects the fact that the outflow being measured may have a limited relationship to inflow in BMPs that have a permanent pool. For example, if a permanent pool is sized to store a volume equal to the average storm, about 60 to 70 percent of storms would be less than this volume [from studies conducted using SYNOP (EPA 1989)].

Table B.4: Example of Individual Storm Loads Method results for TSS in the Tampa Office Pond

Period of Record	Efficiency
1990	29%
1993-1994	-2%
1994-1995	89%

Summary and Comparison of Historical Methods

The table below shows the results of the various historical methods shown above for calculating efficiency for the Tampa Office Pond. The four methods demonstrated (mean concentration method was not applicable to data available from the Tampa Office Pond study) vary widely in their estimates of percent removal depending on the assumptions of each method as discussed above.

Table B.5: Comparison of BMP efficiency methods.

	Method			
Design	**Efficiency Ratio (ER)**	**Summation of Loads (SOL)**	**Regression of Loads (ROL)**	**Efficiency of Individual Storms**
1990	59%	71%	79%	29%
1993-1994	64%	66%	82%	-2%
1994-1995	95%	94%	95%	89%

Other Methods and Techniques

"Irreducible Concentration" and "Achievable Efficiency"

As treatment occurs and pollutants in stormwater become less concentrated, they become increasingly hard to remove. There appears to be a practical limit to the effluent quality that any BMP can be observed to achieve for the stormwater it treats. This limit is dictated by the chemical and physical nature of the pollutant of concern, the treatment mechanisms and processes within the BMP, and the sensitivity of laboratory analysis techniques to measure the pollutant. This concept of "irreducible concentration" has significant implications for how BMP efficiency estimates are interpreted. However, it is possible to get concentrations as low as desired, but in most cases achieving extremely low effluent concentrations may not be practical (i.e., would require treatment trains or exotic methods). For example, colloids are typically viewed as "never" being able to be removed in a pond (settling is the primary mechanism for treatment in ponds), despite the fact that they could be further removed through chemical addition.

The term "irreducible concentration" (C*) has been used in stormwater literature (Schueler 2000) to represent the lowest effluent concentration for a given parameter that can be achieved by a specific type of stormwater management practice. Schueler examined the effluent concentrations achieved by stormwater management practices from published studies for several parameters. From this research, the following estimates of "irreducible concentrations" for TSS, Total Phosphorous, Total Nitrogen, Nitrate-Nitrogen, and TKN for all stormwater management practices were proposed:

Table B.6: "Irreducible concentrations" as reported by Schueler, 2000

Contaminant	Irreducible Concentration
TSS	20 to 40 mg/L
Total Phosphorous	0.15 to 0.2 mg/L
Total Nitrogen	1.9 mg/L
Nitrate-Nitrogen	0.7 mg/L
TKN	1.2 mg/L

Recent research (ASCE 2000) indicates that achievable effluent concentrations vary appreciably between BMP types. For example, in many cases, well-designed sand filters can achieve lower effluent concentrations of TSS than well-designed detention facilities or grassed swales. However, sand filters have issues with long-term maintenance of flow treatment volumes.

The typical approach to reporting the ability of a BMP to remove pollutants from stormwater entails comparing the amount of pollutant removed by the BMP to the total quantity of that pollutant. The concept of irreducible concentration, however, suggests that in some cases it may be more useful to report the efficiency of the BMP relative to some achievable level of treatment (i.e. express efficiency as the ability of the BMP to remove the fraction of pollutant which is able to be removed by a particular practice.)

The following example illustrates this approach. Suppose that two similar BMPs have been monitored and generated the following results for TSS:

Table B.7: Example TSS results for typical ER Method

Percent TSS Removal Using Absolute Scale		
	BMP A	**BMP B**
Influent Concentration	200 mg/L	60 mg/L
Effluent Concentration	100 mg/L	30 mg/L
Efficiency Ratio	50%	50 %

Clearly, the effluent from BMP B is higher quality than that from BMP A, however comparing percent removals between BMPs alone would indicate that both BMPs have an equal efficiency. Methods have been suggested for quantifying the dependence of BMP efficiency on influent concentration. The following section presents one such method advanced by Minton (1998).

In order to account for the dependence of BMP efficiency on influent concentration, Minton (1998) suggests a method of evaluating BMP efficiency that would recognize the relationship between influent concentration and efficiency. The relationship is summarized as follows:

$$\text{Achievable Efficiency} = (C_{\text{influent}} - C_{\text{limit}}) / C_{\text{influent}}$$

where,

C_{influent} : Influent Concentration of Pollutant; and

C_{limit} : The lower attainable limit concentration of the BMP (e.g., “irreducible concentration” or value obtained from previous monitoring of effluent quality)

For example, if a BMP had a lower treatment limit of TSS at 20mg/L concentration, then at an influent TSS concentration of 100 mg/L, it would be assigned an equivalent performance of 80%, while at an influent TSS concentration of 50 mg/L the equivalent performance would be 60%.

This method relies on the ability to determine the lower attainable limit concentration, which is analogous to the “irreducible concentration” for a specific BMP, however effluent quality is best described not as a single value, but from a statistical point of view (See the Effluent Probability Method).

The Achievable Efficiency may be useful in better understanding the results of the ER method in cases where the influent concentration is lower than is typically observed.

Alternately, a single factor (dubbed the Relative Efficiency here) can be used to report how well a BMP is functioning during some period relative to what that BMP is theoretically or empirically able to achieve (as defined by the Achievable Efficiency).

As shown below, the Relative Efficiency can be found by dividing the Efficiency Ratio by the Achievable Efficiency, thus yielding an estimate of how well the BMP performed relative to what is "achievable".

$$\text{Relative Efficiency} =$$

$$\frac{\text{Efficiency Ratio}}{\text{Achievable Efficiency}} = \frac{[(C_{\text{influent}} - C_{\text{effluent}})/C_{\text{influent}}]}{[(C_{\text{influent}} - C_{\text{limit}})/\ C_{\text{influent}}]}$$

Or simplifying:

$$\text{Relative Efficiency} = (C_{\text{influent}} - C_{\text{effluent}})/(C_{\text{influent}} - C_{\text{limit}})$$

If applied to the example presented earlier in this section, the following results are obtained:

Table B.8: Example TSS results for demonstration of Relative Efficiency approach

	BMP A	**BMP B**
Influent Concentration	200 mg/L	60 mg/L
C_{limit}	20 mg/L	20 mg/L
Effluent Concentration	100 mg/L	30 mg/L
Relative Efficiency	56%	75 %

For this example, the results indicate that BMP B is achieving a higher level of treatment than BMP A and this approach may be more useful as a comparative tool than the Efficiency Ratio for some data sets. The Relative Efficiency for a BMP's effectiveness is still influenced by influent concentration but less so than is the Efficiency Ratio.

As C_{influent} approaches C_{limit} the Relative Efficiency goes to infinity, which is not a very meaningful descriptor. However, if the influent concentration is near the "irreducible concentration" for a particular pollutant, very little treatment should occur and $C_{\text{influent}} - C_{\text{effluent}}$ should approach zero. C_{effluent}, at least theoretically, should always be higher than C_{limit} and the numerator of the equation should approach zero faster than the denominator. If C_{influent} is less than C_{limit}, the Relative Efficiency approach should not be used. As is always the case, any of the percent removal efficiency approaches (including the Efficiency Ratio Method) should not be employed if there is not a statistically significant difference between the average influent and effluent concentrations.

If this method is used to represent data from more than one event (i.e., mean EMCs are calculated) it should be supplemented with an appropriate non-parametric (or if applicable parametric) statistical test indicating if the differences are statistically significant (it would be preferred to show the actual level of significance found, instead of just noting if the result was significant, assuming a 0.05 level).

Percent Removal Relative to Water Quality Standards

From a practical or programmatic perspective, it may be more useful to substitute the water quality limit for the "irreducible concentration" as a measure of how well the BMP is meeting specific water quality objectives. A measure of efficiency can be calculated to quantify the degree to which stormwater BMPs employed are meeting or exceeding state or federal water quality criteria or standards for the runoff they treat.

Standards are enforceable regulations established within the context of an NPDES permit or a TMDL and are usually specific to the receiving water. Water quality criteria are more general guidelines expressed as constituent concentrations, levels, or narrative statements, representing a quality of water that supports a particular beneficial use.

By showing that stormwater is being treated to a level that is higher than standards require or criteria recommend, a permitee may be able to demonstrate to regulators or stakeholders that their current stormwater management practices are adequate for a particular constituent of concern. The equation to calculate the Percent Removal Relative to Receiving Water Quality Limits is as follows:

$$\text{Percent Removal Relative to Receiving Water Quality Limits} =$$

$$(C_{\text{influent}} - C_{\text{effluent}})/(C_{\text{influent}} - C_{\text{standard/criterion}})$$

The following example illustrates the application of this approach for reporting efficiency:

Table B.9: Example of percent removal relative to receiving water quality limits approach

	BMP A
Influent Concentration (EMC)	1.65 ug/l
$C_{\text{standard/criterion}}$	0.889 ug/l
Effluent Concentration (EMC)	0.635 ug/l
Percent Removed Relative to Established WQ Limits	133 %

The results indicate that the BMP for the given event is meeting the water quality standard or criterion for dissolved lead. In fact the BMP is functioning to remove in excess of the amount needed to bring the influent concentration below the water quality limit (as indicated in the example by a value greater than 100%). Use of this method is only recommended for specific event analysis. As mentioned for previous analyses, if this approach is taken for a series of events it should be supplemented with an appropriate non-parametric (or if applicable parametric) statistical test indicating if the differences are statistically significant (it would be better to show the actual level of significance found, than just noting if the result was significant, assuming a 0.05 level)

"Lines of Comparative Performance©"

For many stormwater treatment BMPs, the efficiency of the BMP decreases as a function of the influent concentration. Methods have been recommended that integrate this concept into efficiency evaluations. The "Lines of Comparative Performance©" (Minton 1998) is one such method.

In this method, plots of percent removal as a function of the influent concentration for each storm are generated for each pollutant monitored. The results of these plots are overlaid on plots of data collected from studies of similar BMPs within a region.

"Lines of Comparative Performance©" are generated for the data from similar BMPs based on best professional judgment by examining the likely "irreducible concentration" for a particular pollutant, the detection limit for that pollutant, and knowledge of expected maximum achievable efficiency for a BMP type.

This method has primarily been suggested as an approach to evaluate the efficiency of innovative and "unapproved" stormwater technologies. "To be accepted, the performance data points of an unapproved treatment technology must fall above and to the left of the 'Line of Comparative Performance©." This approach has several limitations, the most significant of which is self-correlation.

An alternate method which does not include some of the significant problems associated with the "Lines of Comparative Performance©", but presents relatively the same information can be generated using a simple plot of effluent concentration as a function of influent concentration with "rays" (or curves on a log plot) originating from the plot origin for several levels of control (e.g., 0, 25, 50, 75, and 90%). The plot may need to be a log-log plot for data with a large range of values typical of stormwater monitoring data.

Multi-Variate and Non-Linear Models

Reporting efficiency as a percent removal that is calculated based on the difference between influent and effluent concentrations will always make a BMP that treats higher strength influents appear to be more efficient than one treating weaker influents if both are achieving the same effluent quality. A more useful descriptor of efficiency would take into consideration that weaker influents are more difficult to treat than concentrated ones. A multi-variate equation that includes corrections to compensate for this phenomena or a non-linear model may be worth considering for reporting efficiency.

A model that approaches pollutant removal in a manner similar to the reaction rates for complex physical and chemical batch and plug-flow processes may be useful. To date calibration of such a model for all but the most elementary situations (e.g., settling of solids in relatively simplistic flow regimes) is difficult given the complexity of the real-world problem. As more high quality data becomes available, other approaches to evaluating BMP efficiency may become apparent.

Effluent Probability Method (Recommended Analysis Approach)

The Effluent Probability Method is the recommended analysis approach that is described in Chapter 7 of this manual.

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APPENDICES C THROUGH F

APPENDIX C

ERROR ANALYSIS

Estimating flow in a pipe or open channel is generally accomplished by measuring two or more variables and relating them with an equation to calculate the flow. The continuity equation relates flow to area and velocity:

$$Q = A \times v \tag{C.1}$$

where,

A: Area
v: Velocity

For a rectangular channel, the cross-sectional area can be calculated as the water depth multiplied by the width of the channel.

$$A = H \times w \tag{C.2}$$

where,

H: Depth
W: Width

Velocity can be directly measured with a mechanical current meter or Doppler technology. Estimating flow in the rectangular channel requires three measured variables; each will have an error associated with it:

$$Q = H \times w \times v \tag{C.3}$$

For depth and width measurements, the accuracy will usually be expressed as absolute error governed by the tolerance of the measuring device (i.e. measured depth ± X cm). For velocity, the error in measurement will most likely be a relative error expressed as a percent of the measured value (i.e. measured velocity ± X %). The total error in the calculated flow measurement will include all of the errors associated with the individual measurements as illustrated in the following example:

Equipment tolerances provided by manufacturers generally are based on laboratory data under ideal conditions (e.g. steady state, laminar flow), which may not be representative of installed conditions. A recent USGS study compared several flow monitoring devices designed specifically for stormwater application, and found the error in the observed measurements ranged from 12 to 28 percent.

The actual error is most likely somewhat less than the maximum error and mathematical formulas have been described by Taylor (1997), which describe how error propagates when variables (with associated errors) are combined.

If variables x_i (for I=1 to n) are measurements with small but known uncertainties δx_i and are used to calculate some quantity q, then δx_i cause uncertainty in q as follows.

If q is a function of one variable, $q(x_1)$, then

$$\delta q = \left| \frac{dq}{dx_1} \right| \delta x_1 \qquad \text{(C.4)}$$

If q is the sum and/or difference of x_is then

$$\delta q = \left[\sum_{i=1}^{n} (\delta x_i)^2 \right]^{1/2} \qquad \text{(for independent random errors) (C.5)}$$

Estimates of δq from Equation C.2 are always less than or equal to:

$$\delta q = \sum \delta x_i$$

where x_i are measured with small uncertainties δx_i.

If q is the product and quotient of x_is then

$$\delta q = \left[\sum_{i=1}^{n} \left(\frac{\delta x_i}{x_i} \right)^2 \right]^{1/2} \qquad \text{(for independent random errors) (C.6)}$$

Estimates of δq from Equation C.6 are always less than or equal to:

$$\delta q = \sum \frac{\delta x_i}{|x_i|} \qquad \text{(C.7)}$$

This approach can be directly applied to the analysis of error propagation. Examples for applying this method to flow measurement follow.

Relative Error in Flow Versus Relative Error in Head

Errors in flow measurements are most often caused by field conditions that are inconsistent with the conditions under which rating curves for flow devices were calibrated. However, even under ideal conditions, errors in flow measurement can be significant. This section discusses calculations for estimating the theoretical error associated with flow measurement equipment under ideal circumstances. It can be seen that errors, particularly in low flow measurements, can be quite large.

Equations relating the head (H) measured in a primary device to discharge (Q) (i.e., Rating Equations) fall into four general forms:

1) $Q = aH^d$
2) $Q = a(H + c)^d$
3) $Q = a(bH + c)^d$
4) $Q = a + b_1 H + b_2 H^2 + b_3 H^3 + \cdots + b_n H^n$

The first rating equation is a straight forward application of error propagation for a power function. This equation is

$$\delta Q = Q\left(d \frac{\delta H}{H} \right) \tag{C.8}$$

Flow and head can only be positive values and the power for Rating Equation 1 is always positive (i.e., flow increases proportionally to head, not decreases), thus the absolute value sign is omitted in the above equation. The relative error in flow equals the relative error in head multiplied by the exponent d.

Rating Equations 2, 3, and 4 require an equation relating the error in flow to the derivative of the flow equation and the error in the measured head, which is:

$$\delta Q = \left| \frac{dQ}{dH} \right| \delta H \tag{C.9}$$

Before applying this equation, the derivatives of Rating Equations 2, 3, and 4 are taken with respect to H.

For Rating Equation 2:

$$\frac{dQ}{dH} = ad(H + c)^{d-1} \tag{C.10}$$

For Rating Equation 3:

$$\frac{dQ}{dH} = abd(bH + c)^{d-1} \tag{C.11}$$

For Rating Equation 4:

$$\frac{dQ}{dH} = b_1 + 2b_2 H^1 + 3b_3 H^2 + \cdots + nb_n H^{n-1} \tag{C.12}$$

Prior to applying the equation to the derivatives of Rating Equations 2, 3, and 4 the equation is modified by dividing each side of the Equation by the flow (Q). This yields an equation for the relative error in the flow on the left hand side.

$$\frac{\delta Q}{Q} = \left|\frac{dQ}{dH}\right| \frac{\delta H}{Q} \tag{C.13}$$

Substituting flow Rating Equation 2 for Q and the derivative of Rating Equation 2 for dQ/dH into the right hand side of the above equation, yields:

$$\frac{\delta Q}{Q} = ad(H+c)^{d-1} \frac{\delta H}{a(H+c)^{d}} \tag{C.14}$$

which reduces to:

$$\frac{\delta Q}{Q} = \frac{d}{\left(1+\frac{c}{H}\right)} \frac{\delta H}{H} \tag{C.15}$$

Equation C.11 relates the relative error in the flow to the relative error in the head.

A similar analysis for Rating Equation 3 yields:

$$\frac{\delta Q}{Q} = \frac{d}{\left(1+\frac{c}{bH}\right)} \frac{\delta H}{H} \tag{C.16}$$

Determining an equation for the relative error for Rating Equation 4 is more cumbersome, but is calculated the same way:

$$\frac{\delta Q}{Q} = b_1 + 2b_2H^1 + 3b_3H^2 + \cdots + nb_nH^{n-1} \frac{\delta H}{a + b_1H + b_2H^2 + b_3H^3 + \cdots + b_nH^n} \tag{C.17}$$

Rearranging yields:

$$\frac{\delta Q}{Q} = \frac{b_1 + 2b_2H^2 + 3b_3H^3 + \cdots + nb_nH^n}{a + b_1H + b_2H^2 + b_3H^3 + \cdots + b_nH^n} \frac{\delta H}{H} \tag{C.18}$$

Equation C.4, C.11, C.12, and C.14 relate the relative error in flow to the relative error in head for four common equations describing flow through a primary device. While the equations can be unwieldy, it is a relatively simple exercise to enter them into a spreadsheet program to estimate the error in flow based on estimated error in head and other variables. Most primary devices have a relatively simple flow equation that is sufficiently accurate throughout most of the flow range for the device, which allows for the use of an error equation related to one of the Rating Equations.

The equations relating the relative error in the estimate of flow to the relative error in the measurement of head can also be expressed in terms of absolute errors by multiplying each side of the equations by Q. For example the flow Equation 3 becomes:

$$Q \times \frac{\delta Q}{Q} = \frac{d}{\left(1 + \frac{c}{bH}\right)} \frac{\delta H}{H} \times a(bH + c)^{d} = abd(bH + c)^{d-1}\,\delta H \qquad \text{(C.19)}$$

An Example of Error Analysis for a BMP

The following example illustrates how estimates of error propagation can be applied to flow measurements. This example assumes a stormwater BMP has two separate sources of inflow and one outflow. The flow measurement devices and errors are listed in Table 1.

Table C.1: Example of inputs for estimation of errors in flow measurement devices

Station	Variable	Equipment	Measured Value or formula	Accuracy
Inlet 1	Width	Tape Measure	3 meters	± 0.025 meters
	Depth	Pressure Transducer	1.2 meters	± 0.007 meters
	Velocity	Doppler	0.071 meters/sec	± 4 %
Inlet 2	Depth	Bubbler	0.12 meters	± 0.001 meters
		0.457 m (1.5') Palmer-Bowlus Flume	Q (L/s) = $1076.4(H + 0.005715)^{1.8977}$	± 3 %
Outlet	Depth	Pressure Transducer	0.70 meters	± 0.007 meters
		45^{o} V notch weir	Q (L/s) = $571.4H^{2.5}$	± 6 %

For Inlet 1, the flow calculation is:

$$Q_{inlet-1} = (3)\,m \times (1.2)\,m \times (0.071)\ m/s$$

$$Q_{inlet-1} = 0.2556\,m^{3}/s$$

The error associated with this measurement can be calculated using the equation for error of products and quotients (i.e., Equation C.6):

Assuming that the errors are independent and randomly distributed, the relative error in q equals:

$$\frac{\delta q}{q} = \sqrt{\left(\frac{\delta w}{w}\right)^{2} + \left(\frac{\delta H}{H}\right)^{2} + \left(\frac{\delta v}{v}\right)^{2}} = 0.0413$$

$$\frac{\delta q}{q} = \sqrt{\left(\frac{.025}{3}\right)^2 + \left(\frac{0.007}{1.2}\right)^2 + (0.04)^2}$$

$$\delta q = 0.2556\, m^3 / s \times 0.0413 = 0.011\ m^3 / s$$

So that:

$$Q_{inlet-1} = 0.2556 \pm 0.011\ m^3 / s$$

For the Palmer-Bowlus Flume installed in **Inlet 2**, the equation that describes flow (L/s) as function of water depth is:

$$Q_{inlet-2} = 1076.4 \times (H + 0.005715)^{1.8977}$$

Therefore:

$$Q_{inlet-2} = 1076.4 \times (0.12 + 0.005715)^{1.8977}$$
$$Q_{inlet-2} = 21.032 L / s = 0.0210\, m^3 / s$$

The error associated with flow measurement above is proportional to the precision of the transducer used to measure the water depth (i.e., $\pm$ 0.007 meters) and the error intrinsic to the primary device (a relative error of 3%). Rating Equation 1 is used for this case; Equation C.8 can be used to determine the magnitude of relative error in the flow measurement as:

$$\frac{\delta Q}{Q} = \frac{d}{\left(1 + \frac{c}{H}\right)} \frac{\delta H}{H}$$

$$\frac{\delta Q}{Q} = \frac{1.8977}{\left(1 + \frac{0.005715}{0.12\, m}\right)} \frac{0.007\, m}{0.12\, m} = 0.11$$

$$\delta Q = 0.021 m^3 / s \times 0.11 = 0.00231\, m^3 / s$$

Relative error for the flume itself also has to be included. Since the error is a function of one variable, it can be calculated using Equation C.4:

$$\delta q = \left|\frac{dq}{dx}\right| \delta x = 0.03 \times 0.021\ m^3 / s = 0.00063\ m^3 / s$$

The total error is therefore the sum of errors associated with the measuring device (Equation C.5).

$$\delta q_{inlet-2(total)} = \sqrt{0.0023^2 + 0.00063^2} = 0.0024\ m^3 / s$$

$$Q_{inlet-2} = 0.0210 \pm 0.0024\, m^3/s$$

For the **Outlet weir**, the flow can be calculated using the following equation:

$$Q = 571.4 \times H^{2.5}$$

$$Q = 571.4 \times 0.70^{2.5} = 234.25 L/s = 0.234\ m^3/s$$

This is also a power function (Rating Equation 1) and the error can be calculated similarly to the equation for the flume:

$$\delta Q = |2.5| \frac{0.007}{0.70} 0.234\, m^3/s = 0.059\, m^3/s$$

The error associated with the weir itself is a single variable as was the flume:

$$\delta q = 0.06 \times 0.234 m^3/s = 0.014\, m^3/s$$

The total error is the sum of the errors associated with the measuring device and is calculated as follows:

$$\delta q_{Outlet(total)} = \sqrt{0.059^2 + 0.014^2} = 0.061\, m^3/s$$

$$Q_{outlet} = 0.234 \pm 0.061\, m^3/s$$

Results of this error analysis are provided below in Table C.2.

Table C.2: Summary of examples demonstrating the propagation of errors in flow measurement

	Flow (m^3/sec)	Total Error (m^3/sec)	Total Relative Error (m^3/sec)
Inlet-1	0.255	±0.011	4%
Inlet-2	0.021	±0.0024	11%
Outlet	0.234	±0.061	26%

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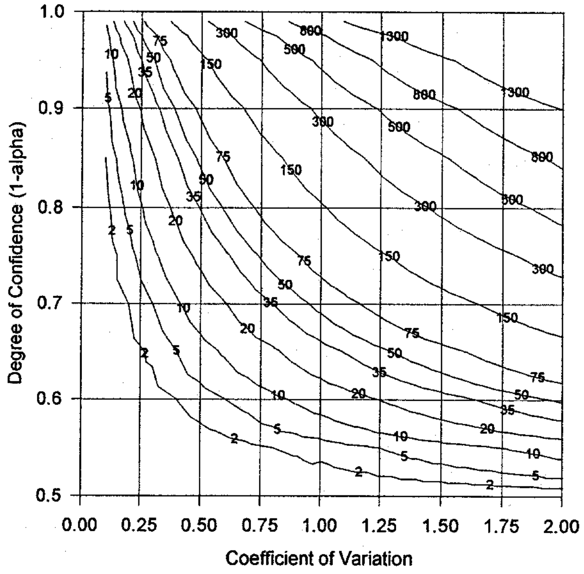
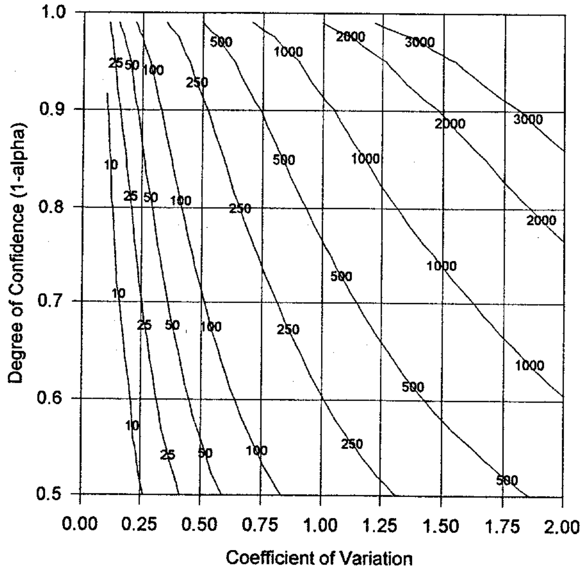
APPENDIX D

NUMBER OF SAMPLES REQUIRED FOR VARIOUS POWERS, CONFIDENCE INTERVALS, AND PERCENT DIFFERENCES

From R. Pitt and K. Parmer. *Quality Assurance Project Plan (QAPP) for EPA Sponsored Study on Control of Stormwater Toxicants*. Department of Civil and Environmental Engineering, University of Alabama at Birmingham. 1995. Reprinted in Burton, G.A. Jr., and R. Pitt. *Stormwater Effects Handbook: A Tool Box for Watershed Managers, Scientists, and Engineers*. ISBN 0-87371-924-7. CRC Press, Inc., Boca Raton, FL. 2002. 911 pages.

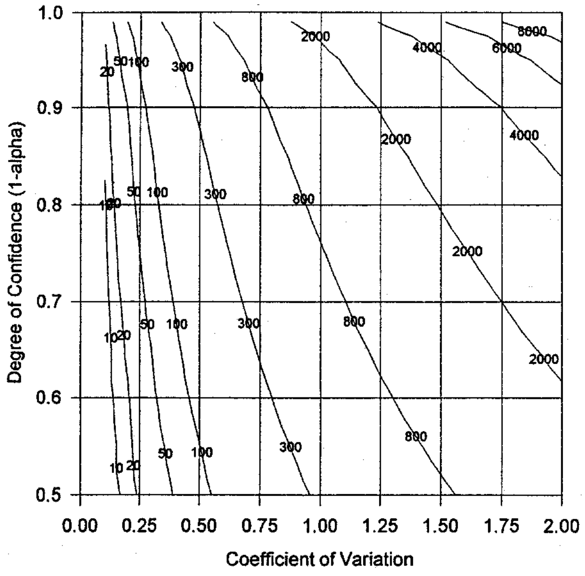


Number of Sample Pairs Needed (Power = 0.5 Difference = 10%)



Number of Sample Pairs Needed (Power = 0.8 Difference = 10%)

Number of Sample Pairs Needed
(Power = 0.9 Difference = 10%)



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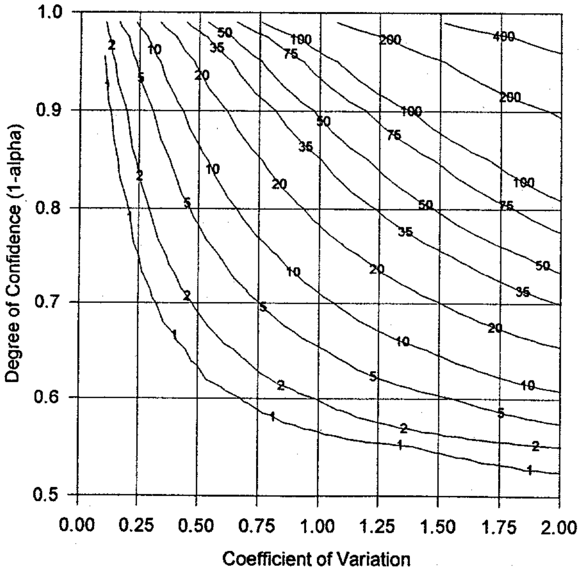

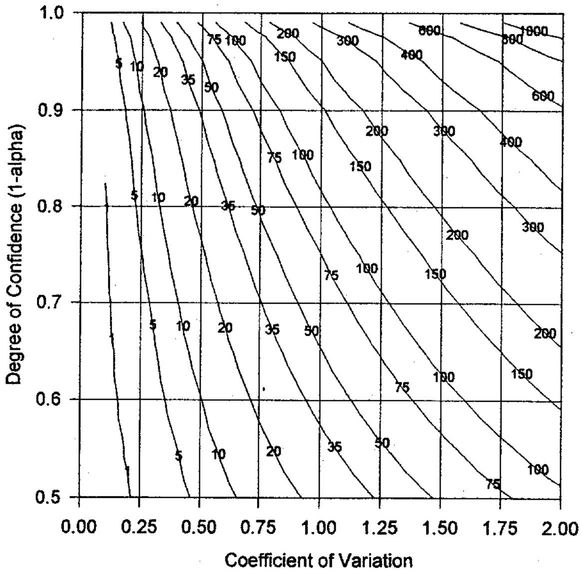

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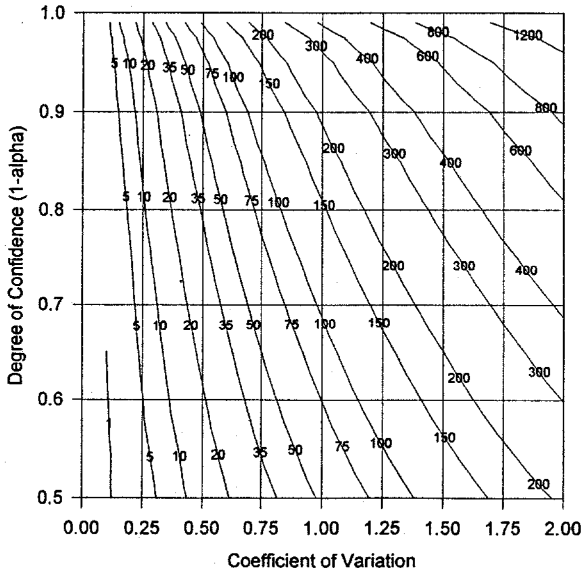
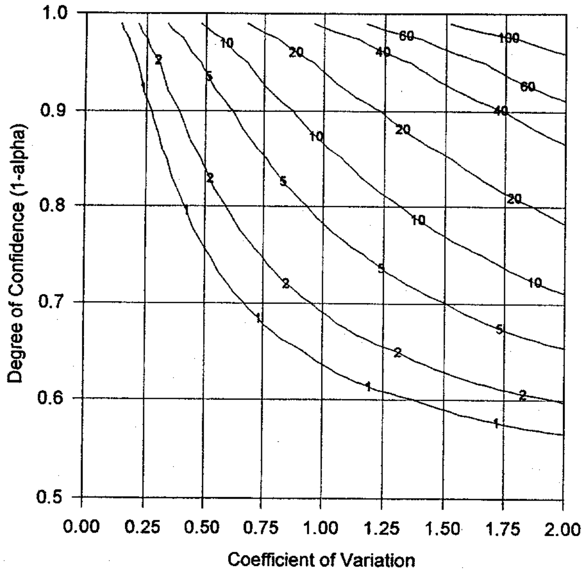


Number of Sample Pairs Needed
(Power = 0.9 Difference = 25%)

Number of Sample Pairs Needed
(Power = 0.5 Difference = 50%)



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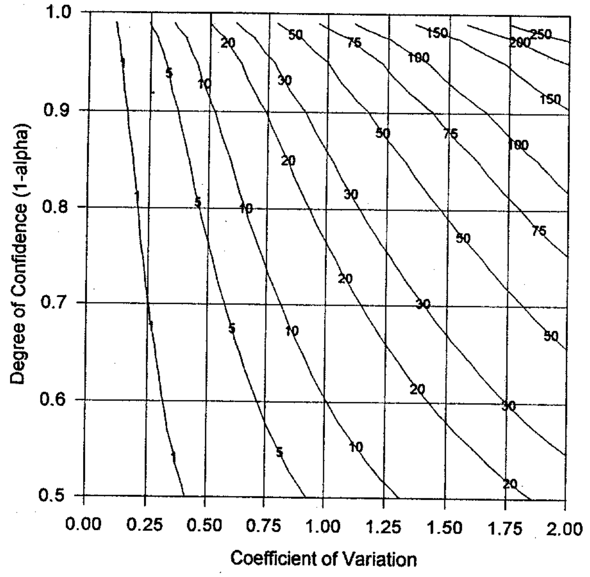

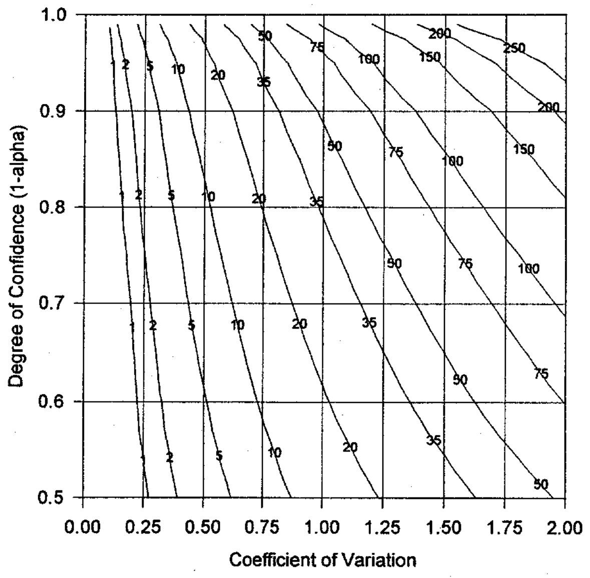

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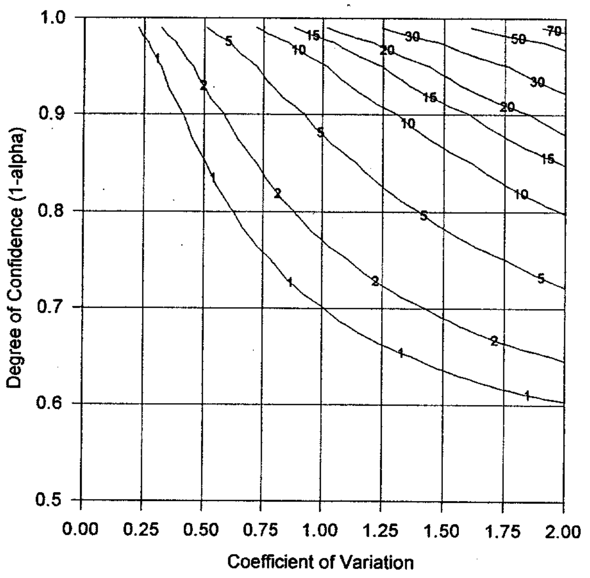
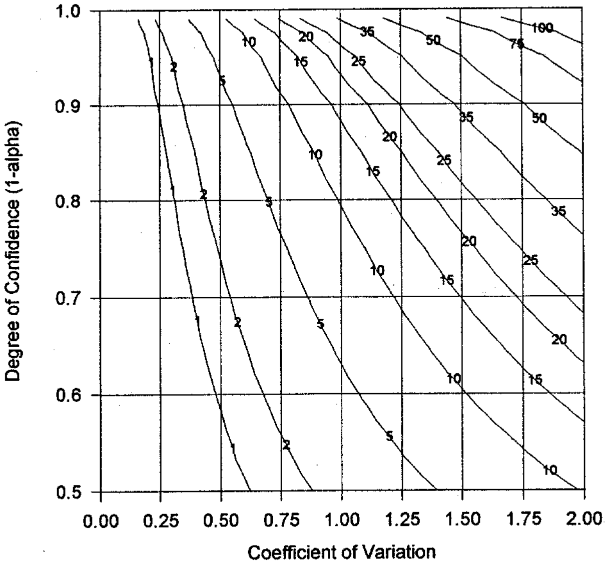


Number of Sample Pairs Needed
(Power = 0.5 Difference = 75%)

Number of Sample Pairs Needed
(Power = 0.8 Difference = 75%)



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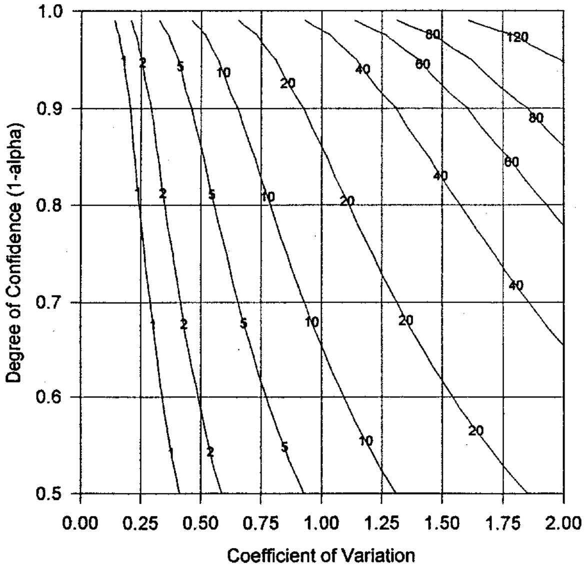
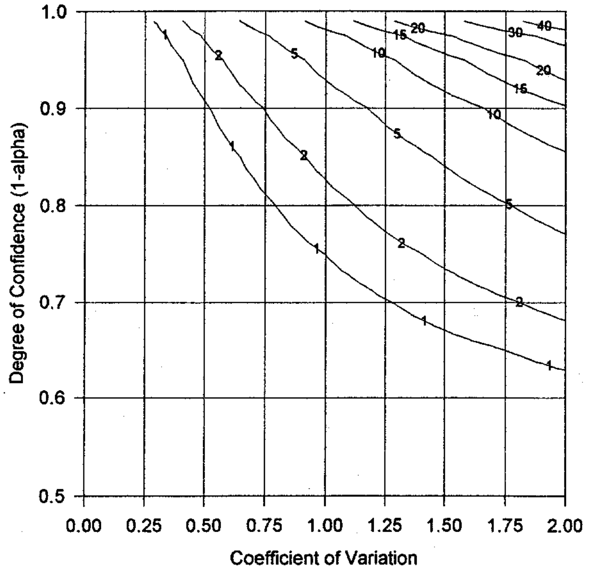
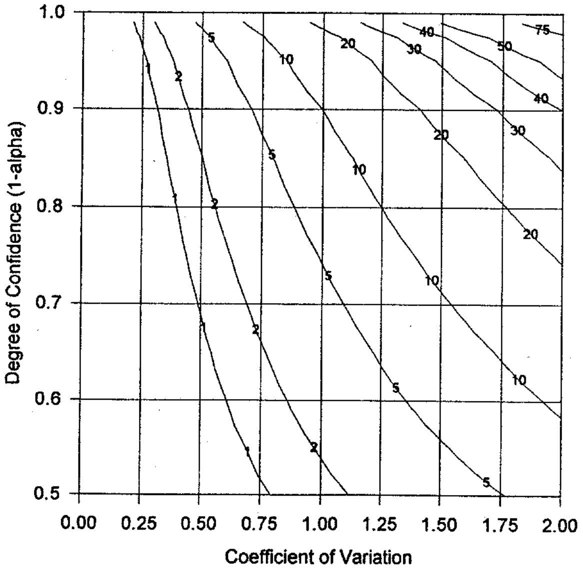


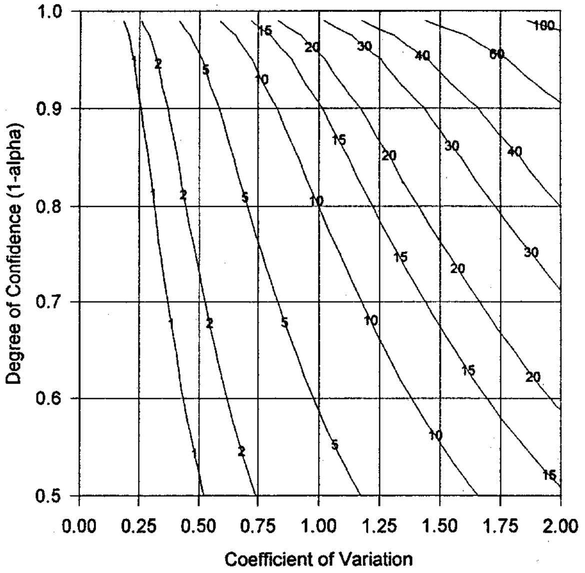
Number of Sample Pairs Needed
(Power = 0.5 Difference = 95%)



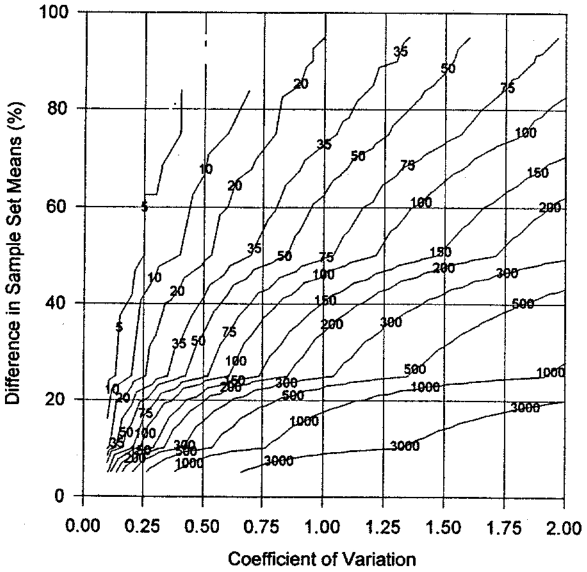
Number of Sample Pairs Needed
(Power = 0.8 Difference = 95%)



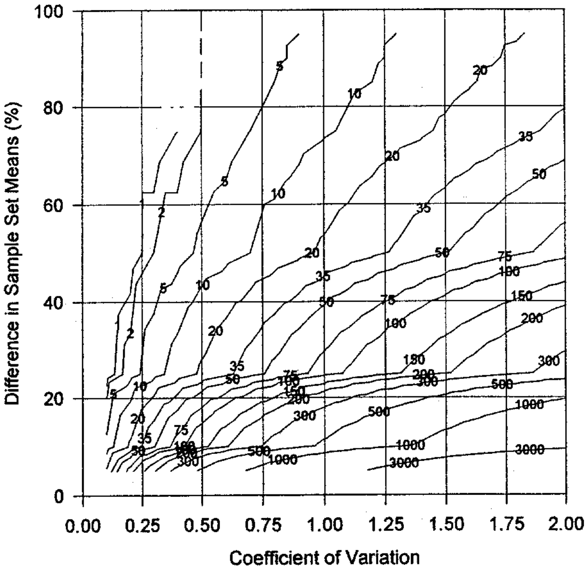
Number of Sample Pairs Needed
(Power = 0.9   Difference = 95%)



Number of Sample Pairs Needed
(Power = 90%   Confidence = 95%)



Number of Sample Pairs Needed
(Power = 50% Confidence = 95%)



APPENDIX E
DERIVATION OF THE NUMBER OF SAMPLES REQUIRED TO MEASURE A STATISTICAL DIFFERENCE IN POPULATION MEANS

Define: COV = $\sigma / \overline{C}$

$$\% \text{ removal} = \left(\overline{C}_{in} - \overline{C}_{out}\right) \Big/ \overline{C}_{in}$$

Setting the lower boundary of the influent confidence interval to the upper boundary of the effluent confidence interval gives:

$$\overline{C}_{in} - Z_{\alpha/2} \frac{\sigma_{in}}{\sqrt{n}} = \overline{C}_{out} + Z_{\alpha/2} \frac{\sigma_{out}}{\sqrt{n}}$$

The COV is substituted for the σ in the above equation. While the σ of a BMP effluent is almost certainly less than the σ of the BMP influent, the assumption that $COV_{in} = COV_{out}$ is a more reasonable one. In most instances the COV of the BMP effluent would be less than the influent. Ample data are available for estimating the COV for influent flows to stormwater BMPs, such as the ASCE database; this is not the case for effluent flows. It is also assumed that n is the same for the influent and effluent ($n_{in} = n_{out}$). These assumptions simplify the equation.

Substituting $\sigma_{in} = COV \times \overline{C}_{in}$ and $\sigma_{out} = COV \times \overline{C}_{out}$, where $COV_{in} = COV_{out}$ yield:

$$\overline{C}_{in} - Z_{\alpha/2} \frac{COV \times \overline{C}_{in}}{\sqrt{n}} = \overline{C}_{out} + Z_{\alpha/2} \frac{COV \times \overline{C}_{out}}{\sqrt{n}}$$

rearranging:

$$\overline{C}_{in} - \overline{C}_{out} = COV \times Z_{\alpha/2} \left(\frac{\overline{C}_{in} + \overline{C}_{out}}{\sqrt{n}} \right)$$

Substituting for $\overline{C}_{out} = \overline{C}_{in} - \overline{C}_{in}(\%removal)$ gives:

$$\overline{C}_{in} \times \%removal = COV \times Z_{\alpha/2} \left(\frac{2 \times \overline{C}_{in} - \%removal \times \overline{C}_{in}}{\sqrt{n}} \right)$$

Dividing both sides by $\overline{C}_{in}$ and solving for n yields:

$$n = \left[\frac{Z_{\alpha/2} \times COV \times (2 - \%removal)}{\%removal} \right]^2$$

The above approach considers the number of samples required for a power of 50%. For an arbitrary power the equation becomes:

$$n = \left[\frac{\left(Z_{\alpha/2} + Z_{\beta/2} \right) \times COV \times \left(2 - \%removal \right)}{\%removal} \right]^2$$

where,

$Z_{\beta/2}$: false negative rate (1-β is the power. If used, a value of β of 0.2 is common, but it is frequently ignored, corresponding to a β of 0.5.)

APPENDIX F

RELATIONSHIPS OF LOG-NORMAL DISTRIBUTIONS

Table F.1

$T = EXP (U)$	$S = M * CV$
$M = EXP (U + 0.5 * W^2)$	$W = SQRT (LN (1 + CV^2)$
$M = T * SQRT (1 + CV^2)$	$U = LN (M/EXP (O.5 * W^2))$
$CV = SQRT (EXP (W^2) - 1)$	$U = LN (M/SQRT (1 + CV^2)$

Parameter designations are defined as:

	Arithmetic	**Logarithmic**
MEAN	M	U
STD DEVIATION	S	W
COEF OF VARIATION	CV	
MEDIAN	T	

LN(x) designates the base e logarithm of the value x
SQRT(x) designates the square root of the value x
EXP(x) designates e to the power x